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(1)

September 1991

M91-104

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Radiation Efficiency and Input Impedance of Monopole Elements with Radial-Wire Ground Planes in Proximity to Earth

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CONTRACT SPONSOR MSR
CONTRACT NO. N/A
PROJECT NO. 91030
DEPT. D085

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ABSTRACT

Plots are presented, of the radiation efficiency and input impedance of a thin quarter-wave monopole element with a radial-wire ground plane in proximity to flat lossy earth, as a function of the number and length of the radial wires, earth permittivity, and location of the earth's surface with respect to the ground plane. Numerical results are from the method-of moments NEC-GS progam developed by Lawrence Livermore National Laboratory.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE		PAGE

FIGURE **PAGE**

FIGURE		PAGE

FIGURE		PAGE

LIST OF TABLES

SECTION 1

RADIATION EFFICIENCY AND INPUT IMPEDANCE OF MONOPOLE ELEMENTS WITH RADIAL-WIRE GROUND PLANES IN PROXIMITY TO EARTH

The modeling, of monopole elements with circular ground planes in proximity to earth, has been greatly enhanced in recent years by the development of Richmond's method-of-moments programs RICHMD3 [1] and RICHMD4 [2] for disk ground planes and Lawrence Livermore National Laboratory's method-of-moments programs NEC-3 [3], [4], [5] and NEC-GS [6], [7] for radial-wire ground planes.

The method-of-moments models have certain advantages over models based on Monteath's compensation theorem [8], [9] or Sommerfeld's attenuation function [10]. These advantages are: (1) current on the ground plane is determined rather than approximated by that for a perfect ground plane; (2) results are valid not only for moderately-large ground planes but for electrically-small ground planes; (3) directive gain and radiation eficiency can each be determined separately rather than being lumped together as a product to yield the antenna power gain; (4) ground plane edge diffraction is not neglected; and (5) analytical conditions on evaluating Sommerfeld's integral (such as requiring an earth relative permittivity $|\varepsilon^*/\varepsilon_0| >> 1$) are avoided.

Numerical results, based on method-of-moments models, have been published for disk ground planes [1], [2] and for radial-wire ground planes [11]. A detailed discussion of the properties of antennas with electrically-small ground planes in proximity to earth has recently been reported [12].

This paper presents additional results for input impedance and new results for radiation efficiency for a thin quarter-wave monopole element with a radial-wire ground plane in proximity to earth.

The numerical data for the plots were supplied by G. J. Burke, of the Lawrence Livermore National Laboratory, using his method-of-moments Numerical Electromagnetics Code NEC-GS. The NEC-GS program is an optimization for radial-wire ground planes of the NEC-3 program for wire elements in proximity to earth. The NEC-GS program utilizes the rotational symmetry in the azimuthal direction, of the antenna element and its ground plane, to achieve program optimization. Validation of the NEC-GS program is discussed in Ref. [13].

The antenna geometry consists of a monopole element, of length h and radius b, on a groundscreen consisting of N equally-spaced radial wires, of length a and radius b_w, at a depth z_0 below a flat earth surface (see figure 1). The earth, with a dielectric constant ε_r and conductivity σ (S/m) at a radian frequency ω (rad/s) and free-space wavelength λ(m), has a complex relative permittivity $\varepsilon^*/\varepsilon_0 = \varepsilon_r - jx$ where x = loss tangent = $\sigma/\omega\varepsilon_0$ $= (\lambda\sigma/2\pi)\,(\mu_0/\varepsilon_0)^{1/2} \approx 60\,\lambda\,\sigma$. The monopole element and radial wires are assumed to have infinite conductivity. The earth constants, loss tangents, and penetration depths, for CCIR 527-1 characteristics of earth in the HF frequency band 3-30 MHz, are summarized in table 1.

Numerical results are presented for parameters with fixed values $h/\lambda = 0.25$, $b/\lambda = 10^{-5}$, $b_w/\lambda = 10^{-5}$, $\varepsilon_r = 15$ and variable values $z_0/\lambda = 10^{-4}, -10^{-4}, -10^{-2}$, x = 1.5, 15, 150, 1500; $2\pi a/\lambda$ = 0 through 3.8, and N = 4, 8, 16, 32, 64, 128.

The radiation efficiency, input resistance, and input reactance are plotted in figures 2 through 13, 14 through 25, and 26 through 37, respectively. The notation for the number of radial wires is identical in figures 2 through 37. Numerical results of the absolute directive gain patterns were not obtained by G. Burke because, for electrically-small ground planes resting on earth, the absolute directive gain is not appreciably different from that of a vertically-polarized Hertzian dipole (with no ground plane) at zero height above earth. Weiner [2] has shown that the absolute directive gain pattern, for quarter-wave elements on disk ground planes resting on earth, varies by less than 1 dBi as the normalized ground plane radius is varied from 0 to 8 wavenumbers.

The radiation effeciency η is the ratio of the far-field radiated power to the available input power. The far-field radiated power is confined to the air medium for an earth conductivity $\sigma > 0$. The radiation efficiency is a measure of the power loss in the earth because the monopole element and radial wires are assumed to have infinite conductivity. The radiation efficiency increases monotonically with increasing number of the radial wires (see figures 2 through 13) and with increasing length of the monopole element (not shown). The radiation efficiency exhibits resonances with increasing wire length for a sparse number of radial wires (see figures 2 through 13).

The input resistance and input reactance asymptotically approach the values for a disk ground plane as the groundscreen density approaches infinity (i.e., as the number of radial wires $N \rightarrow \infty$ as shown in figures 14 through 37). A unique characteristic of radial-wire ground planes is the resonances in input impedance and radiation efficiency that occur for a sparse number of radial wires provided that the earth is not of high conductivity (see figures 14, 18, 22 26, 30, 34). These resonances occur apparently because the currents on the wires are not closely coupled, unlike the case for a high density of radial wires or the case of a disk ground plane. A more detailed discussion of the electrical characteristics of antennas with electrically-small ground planes in proximity to earth is given in Ref. [12].

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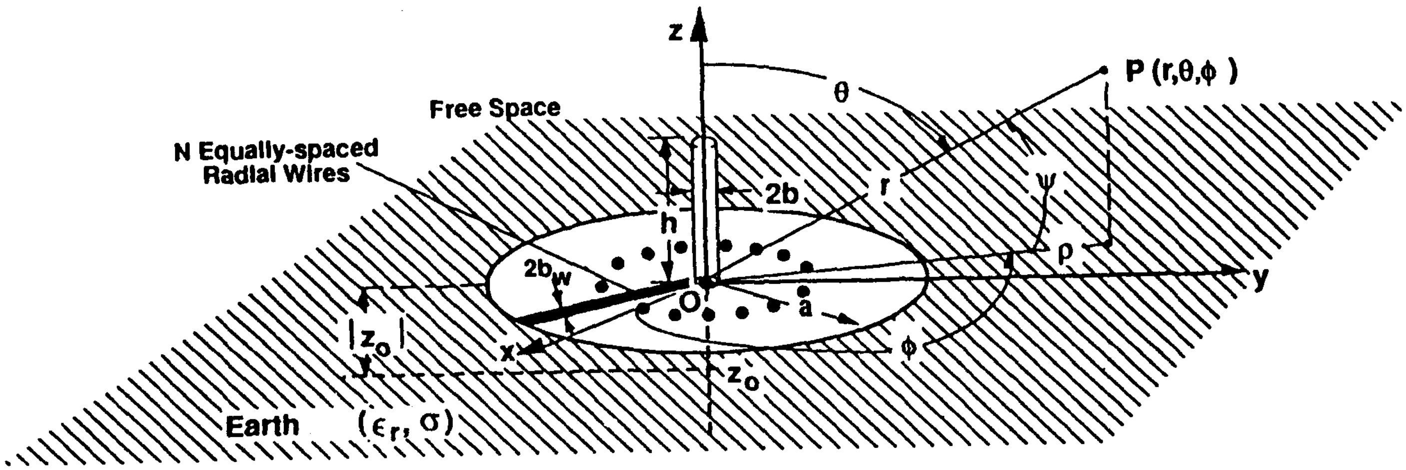

Figure 1. Antenna Parameters

Table 1. Permittivity Constants, Loss Tangent, and Penetration Depth of CCIR 527-1 Classifications of Earth

	CONSTANTS		LOSS TANGENT			PENETRATION DEPTH		
Cases	ε_r	σ (S/*m*)	$\sigma/(\omega\varepsilon_r\varepsilon_0) = (60\lambda)(\sigma/\varepsilon_r)$			δ (*m*)		
			Frequency (MHz) [Wavelength (*m*)]			Frequency (MHz) [Wavelength (m)]		
			3 [99.93]	15 [19.986]	30 [9.993]	3 [99.93]	15 [19.986]	30 [9.993]
(1) Perfect Ground	1.0	∞	∞	∞	∞	0	0	0
(2) Sea Water (average Salinity 20°C)	70.0	5.0	4.282×10^{2}	8.425×10^{1}	4.283×10^{1}	1.3×10^{-1}	5.8×10^{-2}	4.1×10^{-2}
(3) Fresh Water	80.0	3.0×10^{-2}	2.251×10^{0}	4.497×10^{-1}	2.248×10^{-1}	2.1×10^{0}	1.6×10^{0}	1.6×10^{0}
(4) Wet Ground	30.0	1.0×10^{-2}	1.999×10^{0}	3.997×10^{-1}	1.999×10^{-1}	3.7×10^{0}	3.0×10^{0}	2.9×10^{0}
(5) Medium Dry Ground	15.0	1.0×10^{-3}	3.997×10^{-1}	7.995×10^{-2}	3.997×10^{-2}	2.1×10^{1}	2.1×10^{1}	2.1×10^{1}
(6) Very Dry Ground	3.0	1.0×10^{-4}	1.999×10^{-1}	3.997×10^{-2}	1.999×10^{-2}	9.2×10^{1}	9.2×10^{1}	9.2×10^{1}
(7) Pure Water, 20°C	80.0	1.8×10^{-6} 5.0×10^{-4} 1.7×10^{-3}	1.350×10^{-4} - -	- 7.495×10^{-3} -	- - 1.274×10^{-2}	2.6×10^{4} - -	- 9.4×10^{2} -	- - 2.7×10^{1}
(8) Ice (fresh water, -1°C)	3.0	6.0×10^{-5} 9.0×10^{-5} 1.0×10^{-4}	1.199×10^{-1} - -	- 3.597×10^{-2} -	- - 1.999×10^{-2}	1.5×10^{2} - -	- 1.0×10^{2} -	- 9.2×10^{1}
(9) Ice (fresh water, -10°C)	3.0	1.8×10^{-5} 2.7×10^{-5} 3.5×10^{-5}	3.597×10^{-2} - -	- 1.079×10^{-2} -	- - 6.995×10^{-3}	5.1×10^{2} - -	- 3.4×10^{2} -	- - 2.6×10^{2}
(10) Average Land (TCI)	10.0	5.0×10^{-3}	2.998×10^{0}	5.996×10^{-1}	2.998×10^{-1}	4.8×10^{0}	1.6×10^{0}	3.4×10^{0}
(11) Free Space	1.0	0	0	0	0	∞	∞	∞

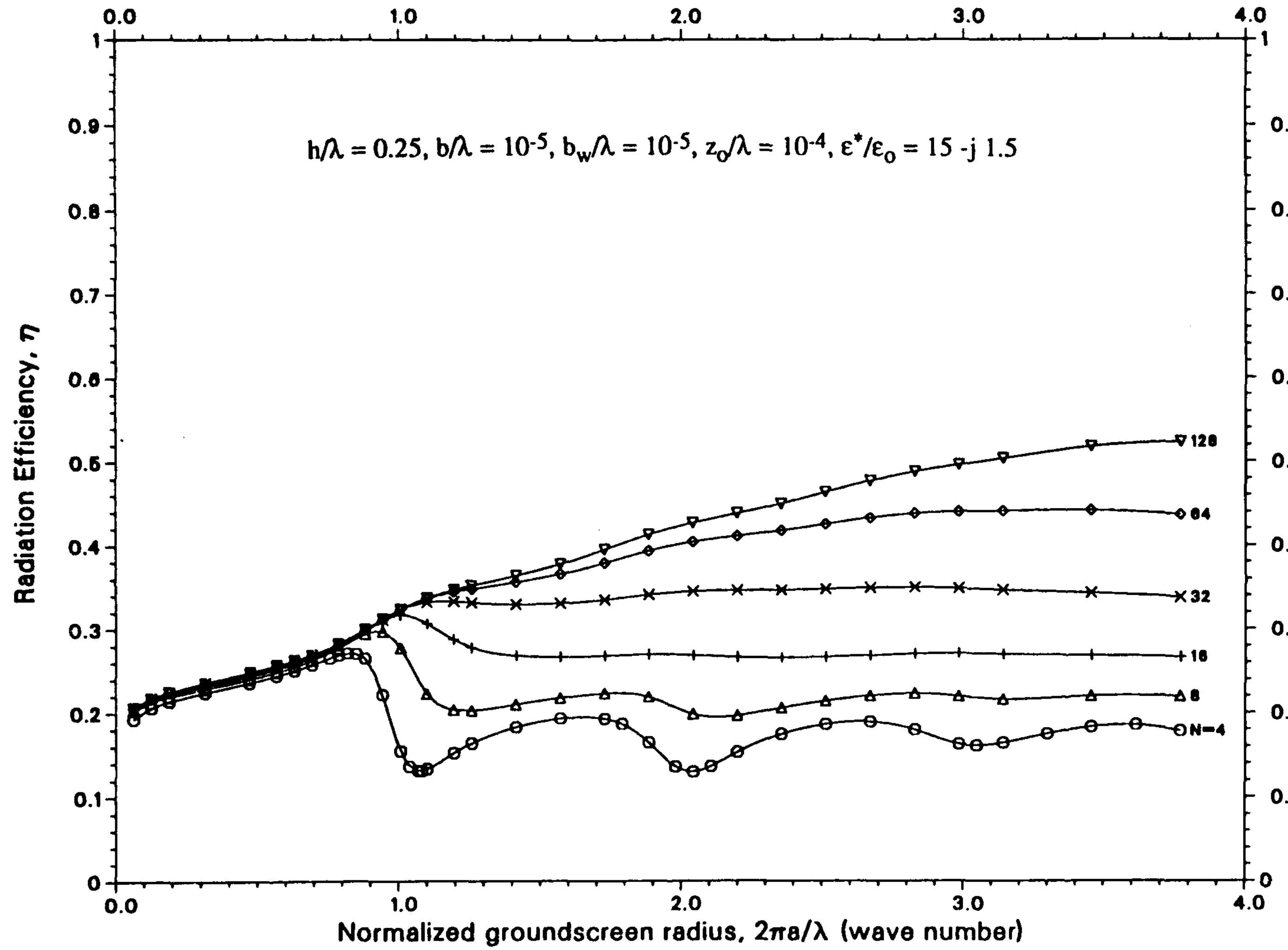

Figure 2. Radiation Efficiency of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Depth $|z_0/\lambda| = 10^{-4}$ Below Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,1.5$

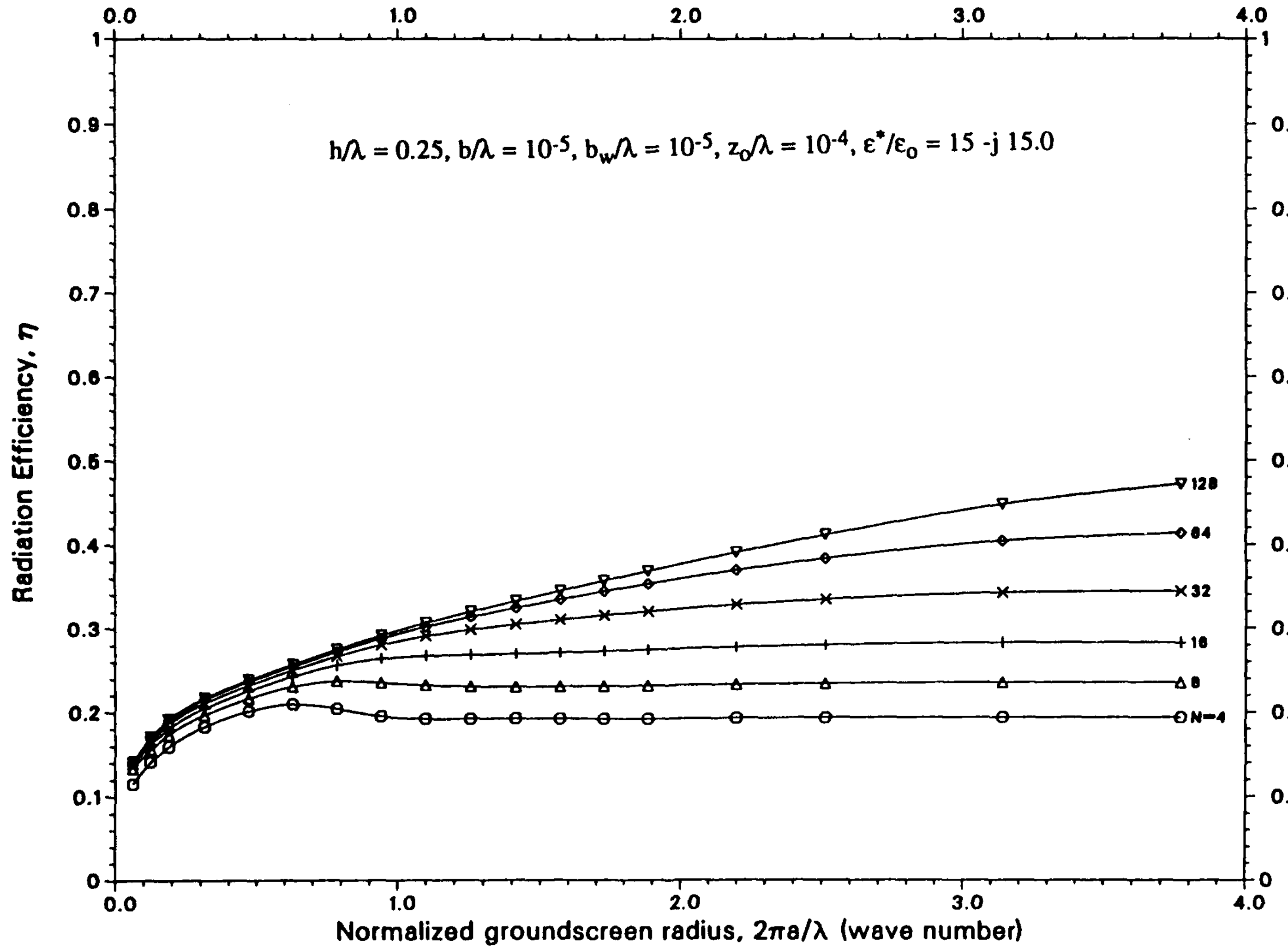

Figure 3. Radiation Efficiency of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Depth $|z_0/\lambda| = 10^{-4}$ Below Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15$ -j 15.0

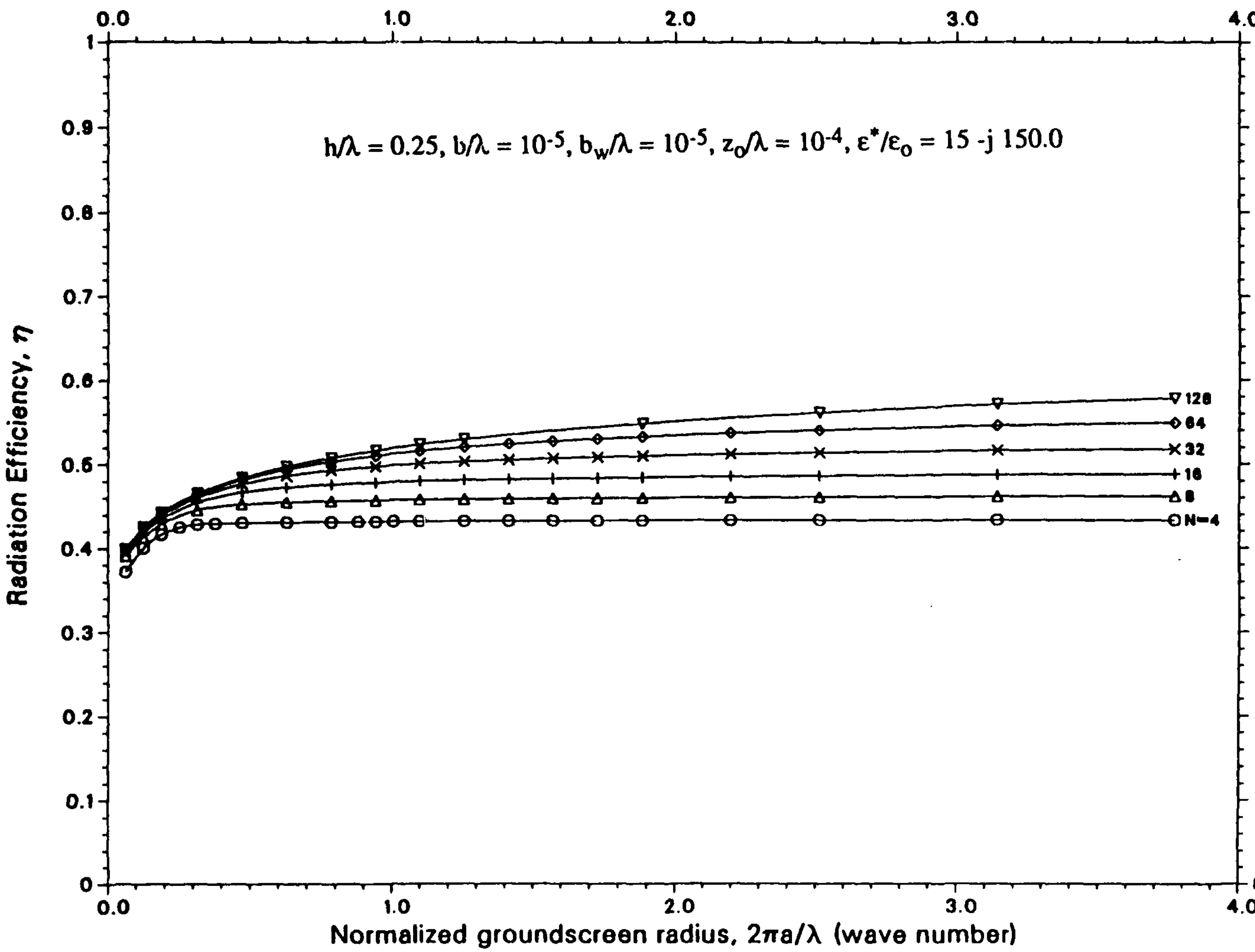

Figure 4. Radiation Efficiency of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Depth $|z_0/\lambda| = 10^{-4}$ Below Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,150.0$

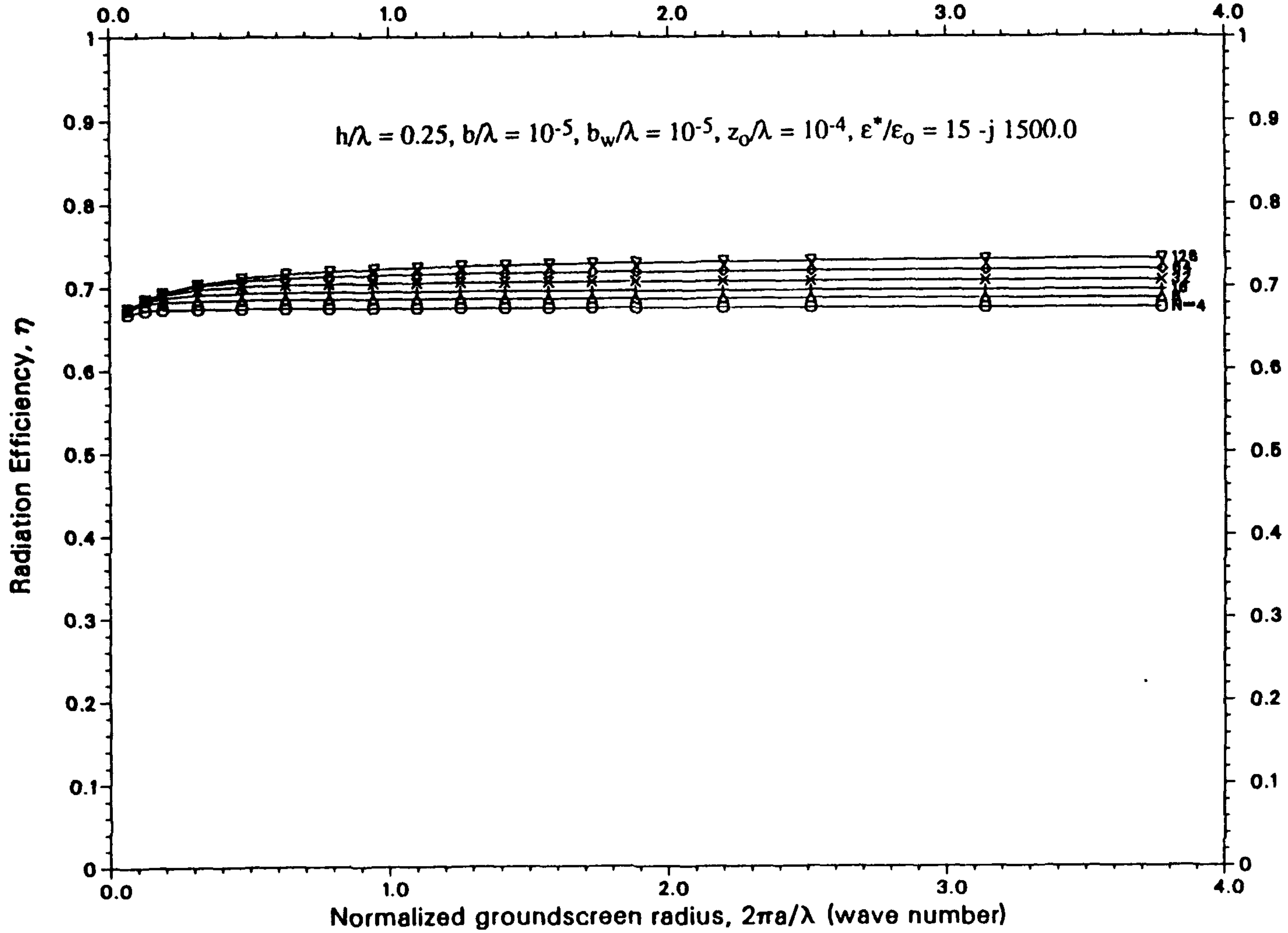

Figure 5. Radiation Efficiency of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Depth $|z_0/\lambda| = 10^{-4}$ Below Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,1500.00$

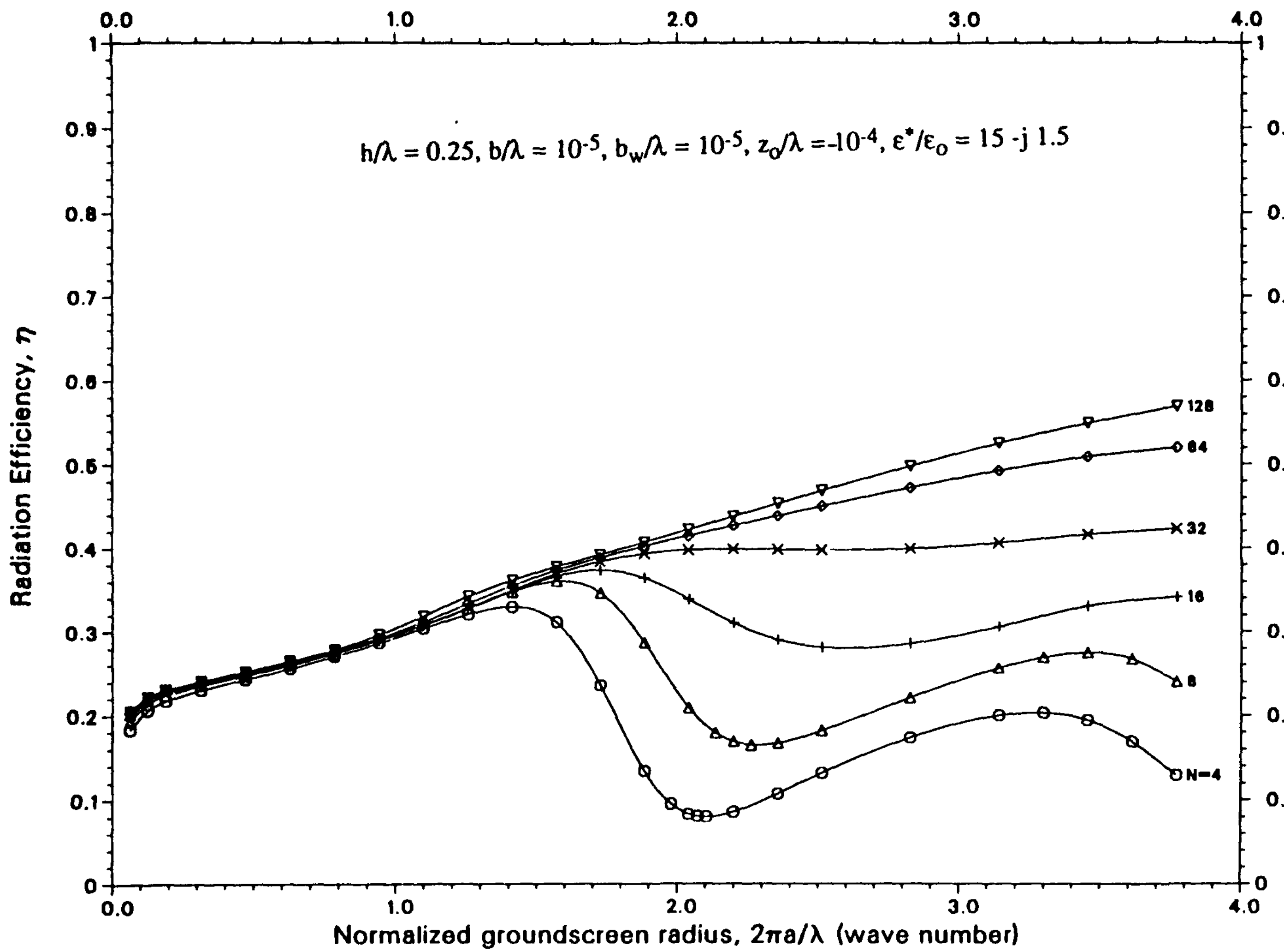

Figure 6. Radiation Efficiency of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-4}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,1.5$

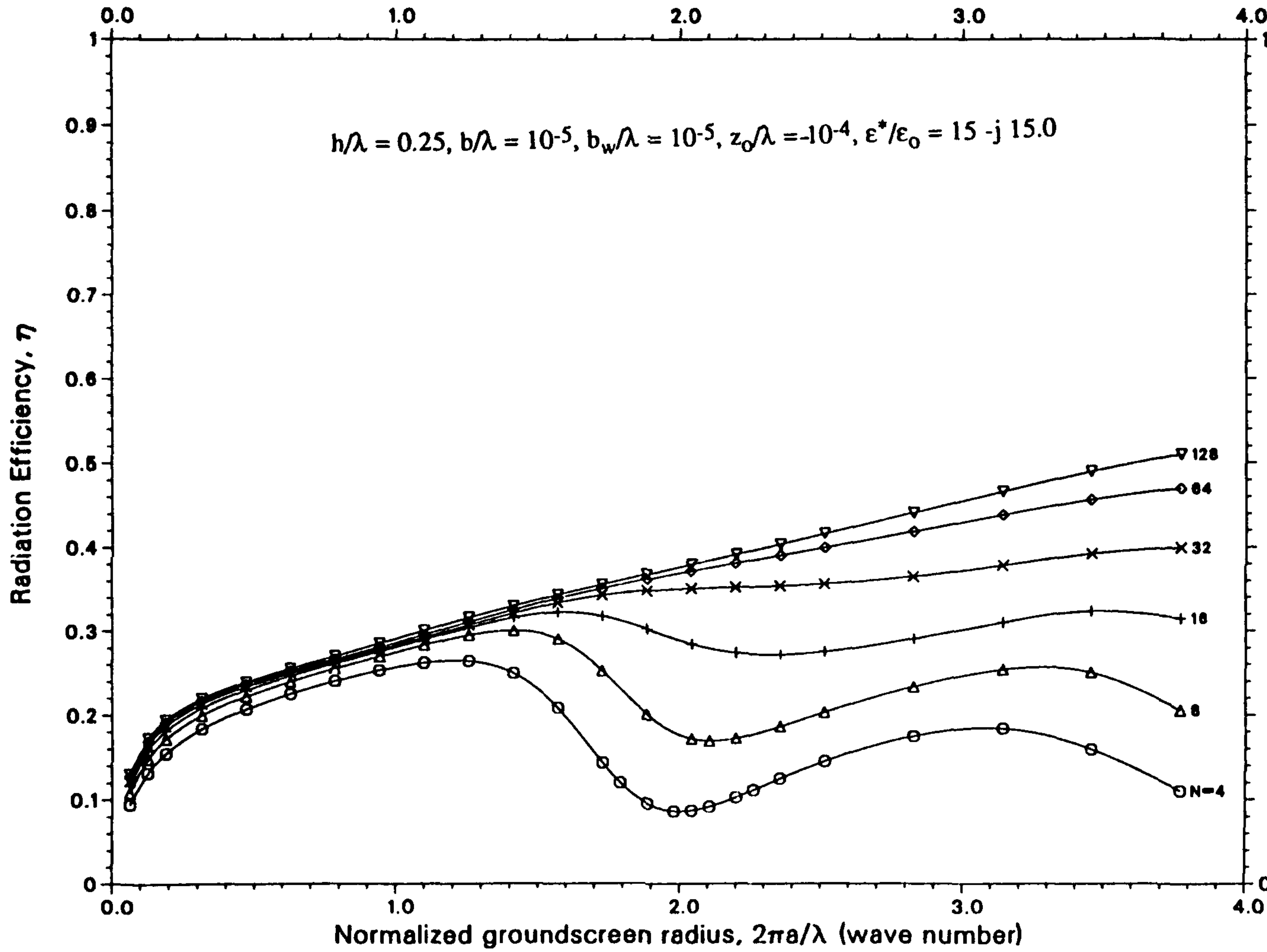

Figure 7. Radiation Efficiency of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-4}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15$ -j 15.0

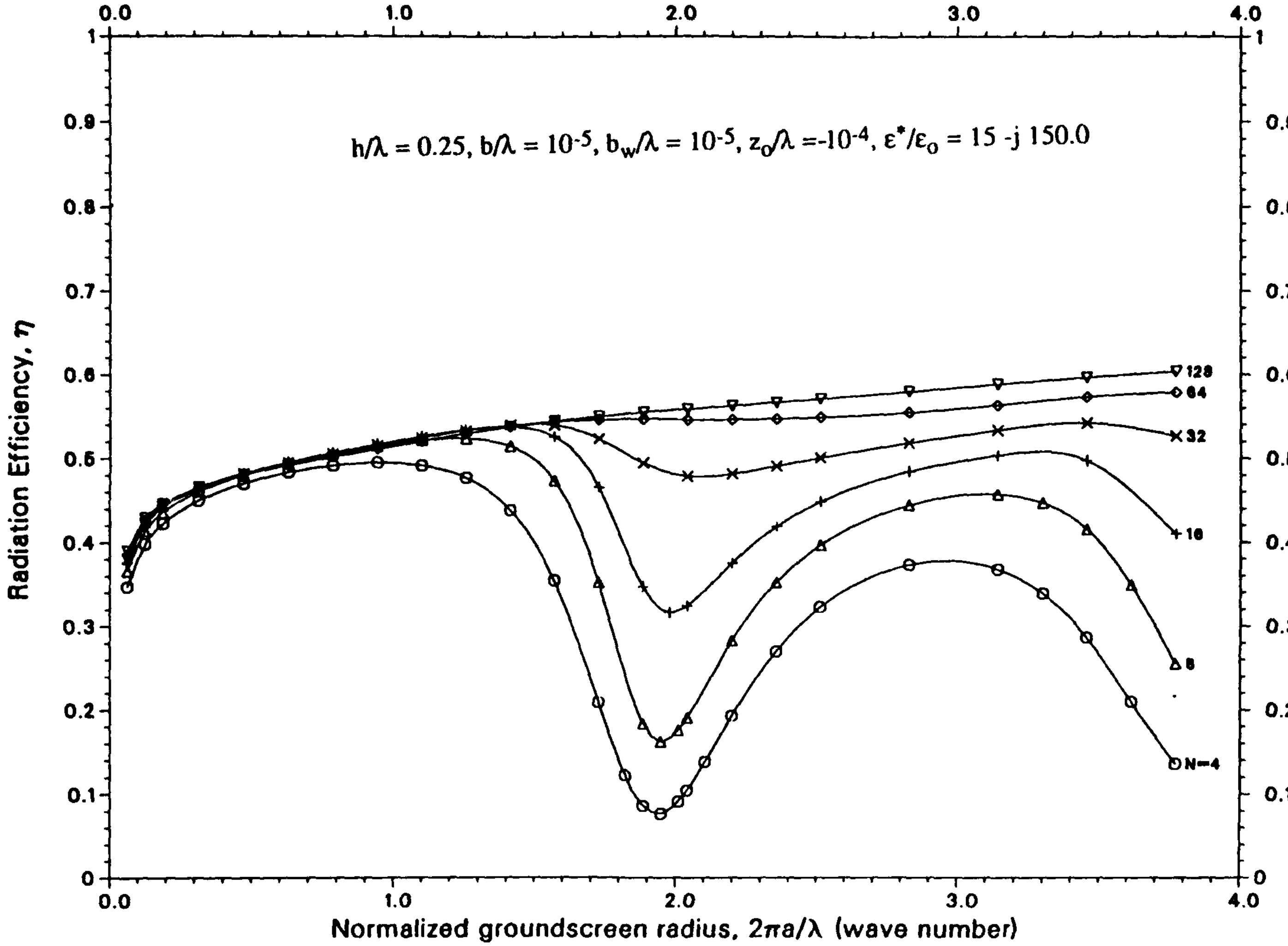

Figure 8. Radiation Efficiency of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-4}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,150.0$

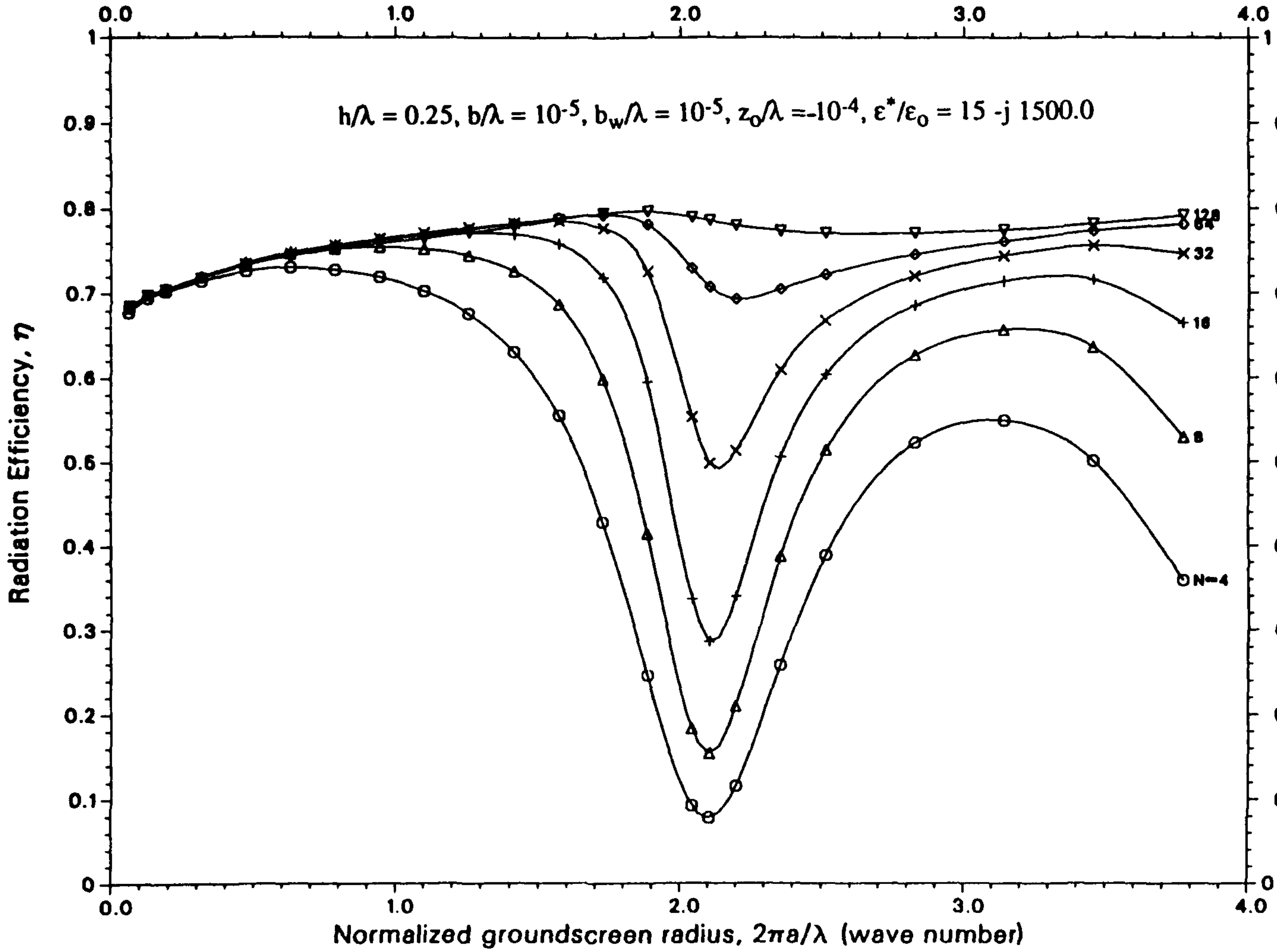

Figure 9. Radiation Efficiency of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-4}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,1500.0$

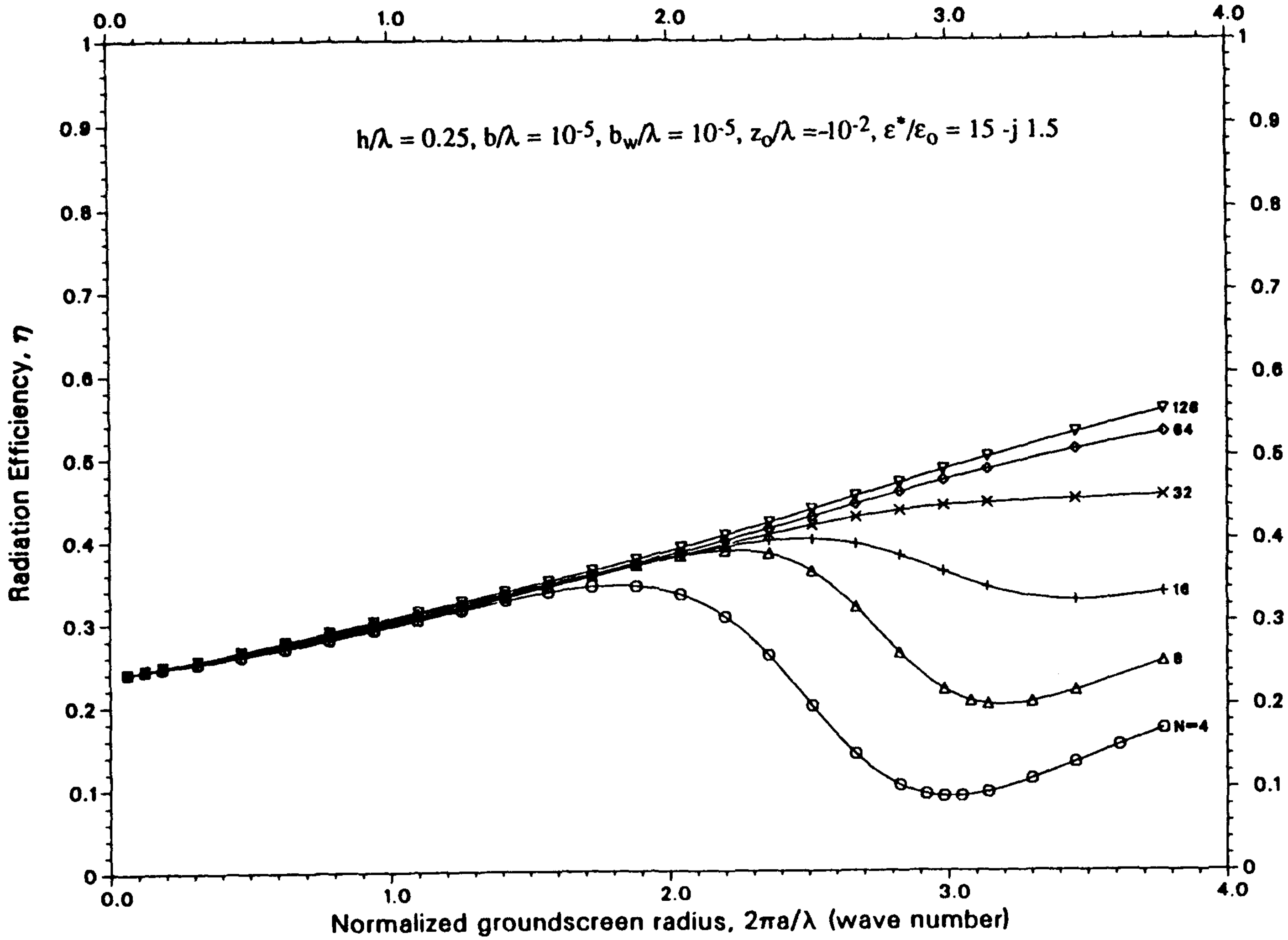

Figure 10. Radiation Efficiency of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-2}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,1.5$

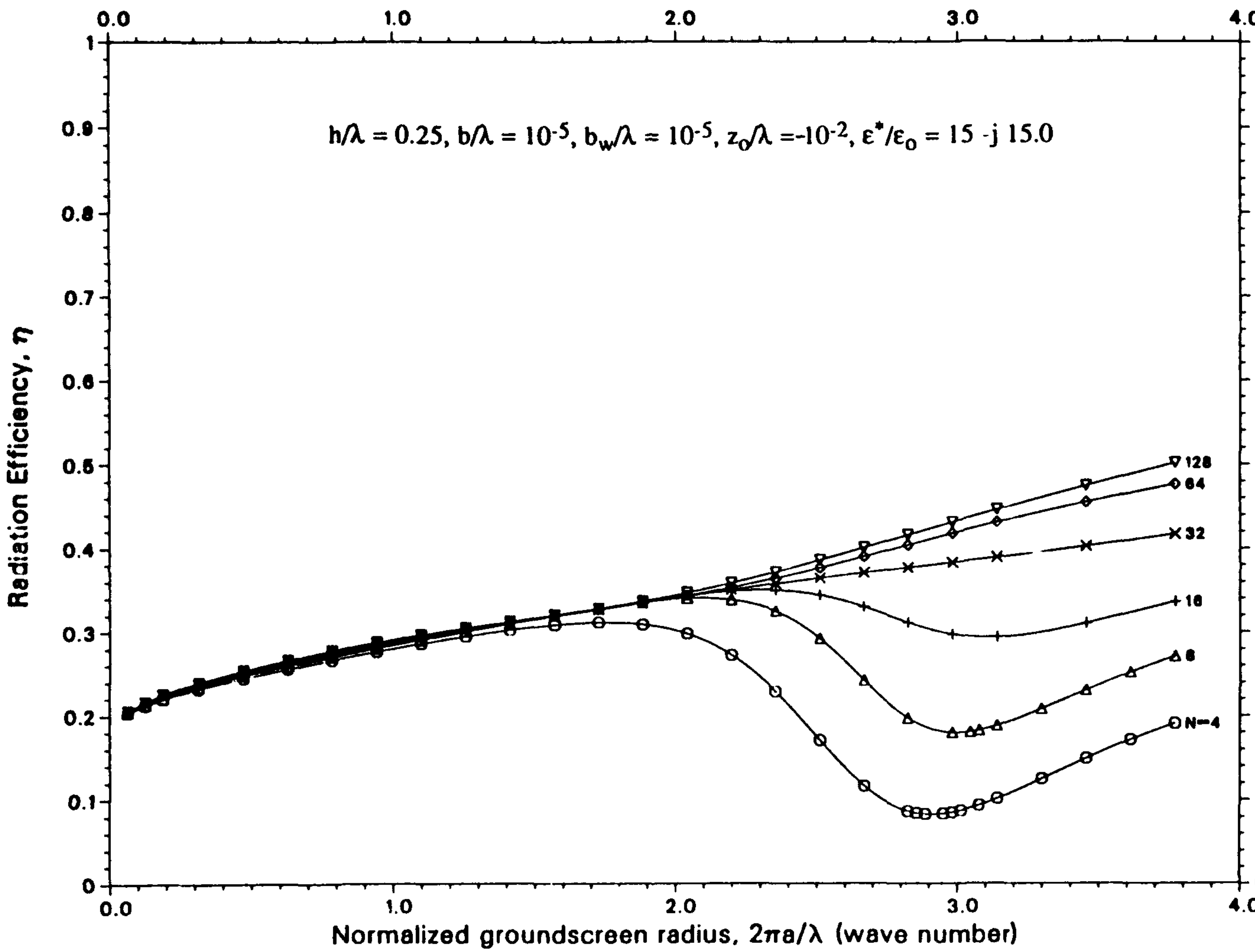

Figure 11. Radiation Efficiency of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-2}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15$ -j 15.0

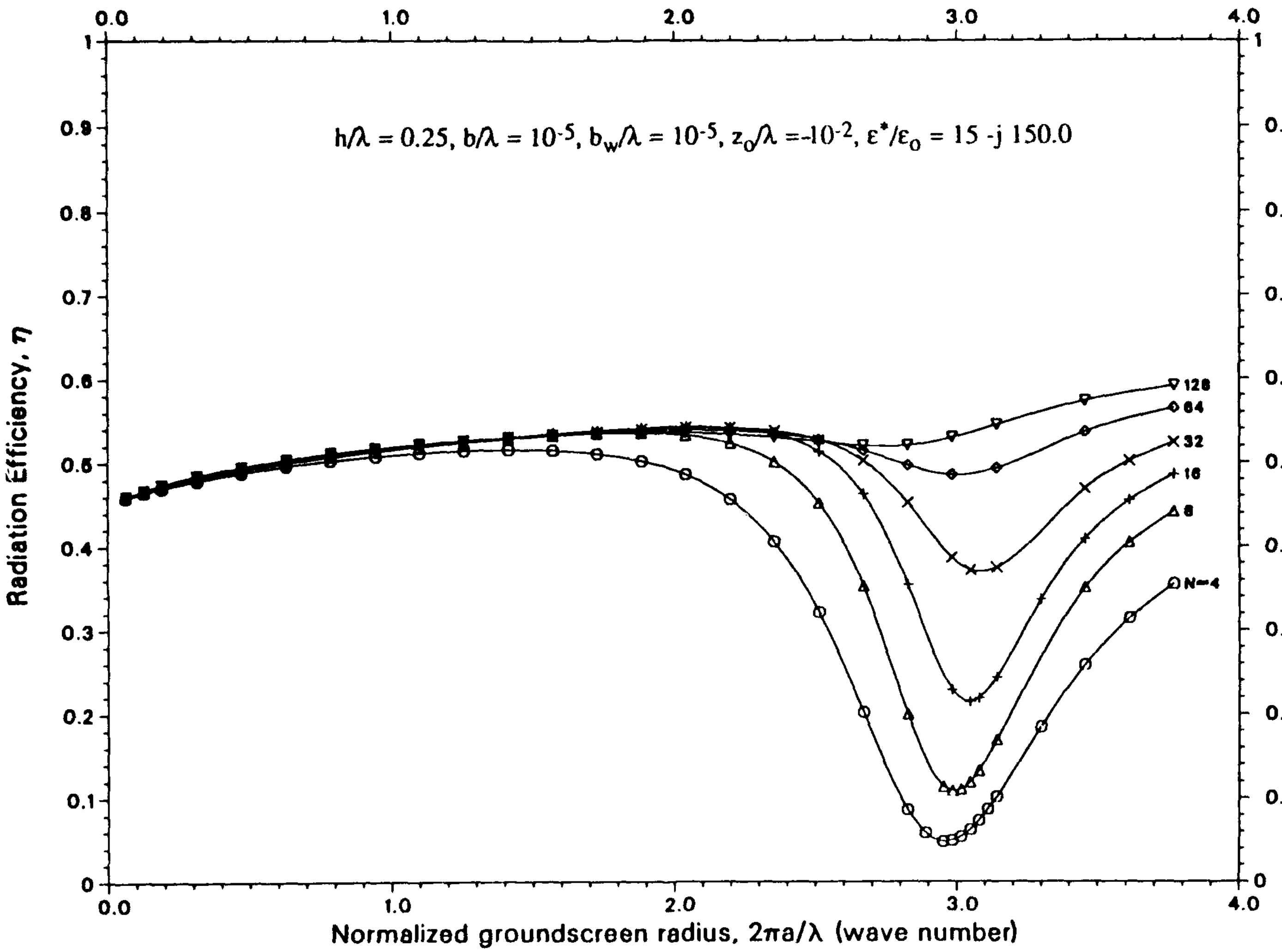

Figure 12. Radiation Efficiency of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-2}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,150.0$

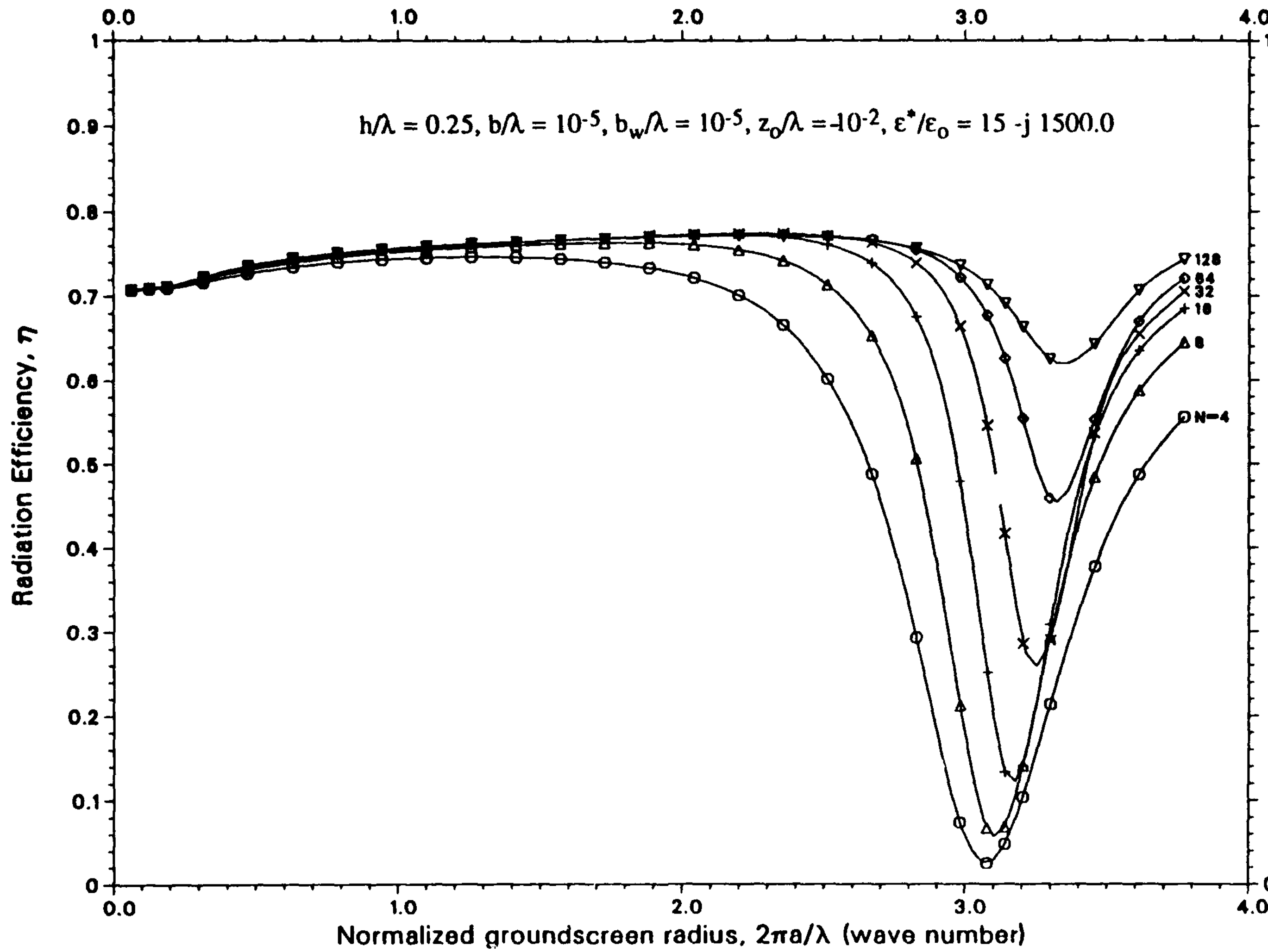

Figure 13. Radiation Efficiency of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-2}$ Above Earth of Relative Permittivity $\epsilon^*/\epsilon_0 = 15 - j\,1500.0$

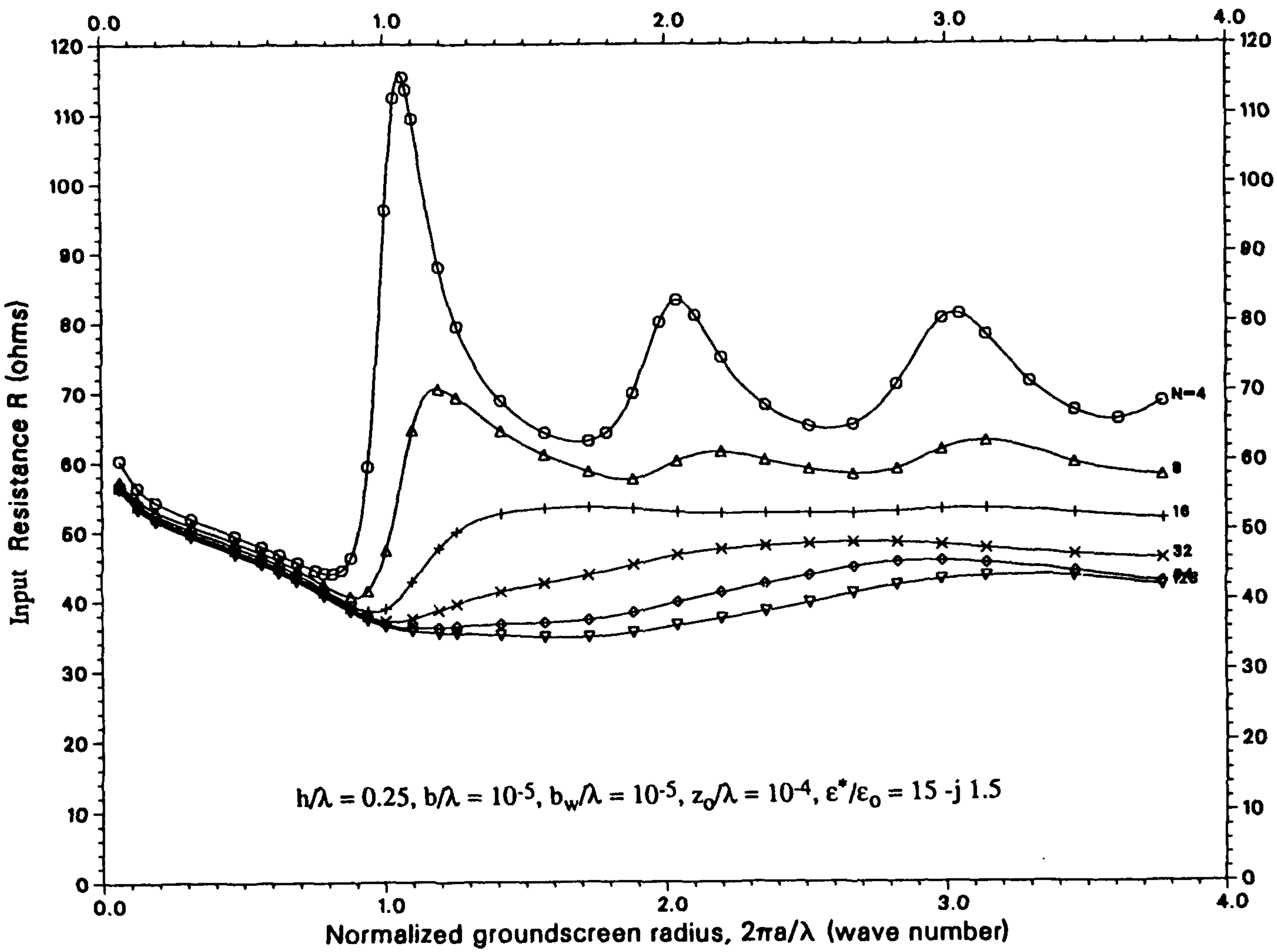

Figure 14. Input Resistance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Depth $|z_0/\lambda| = 10^{-4}$ Below Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,1.5$

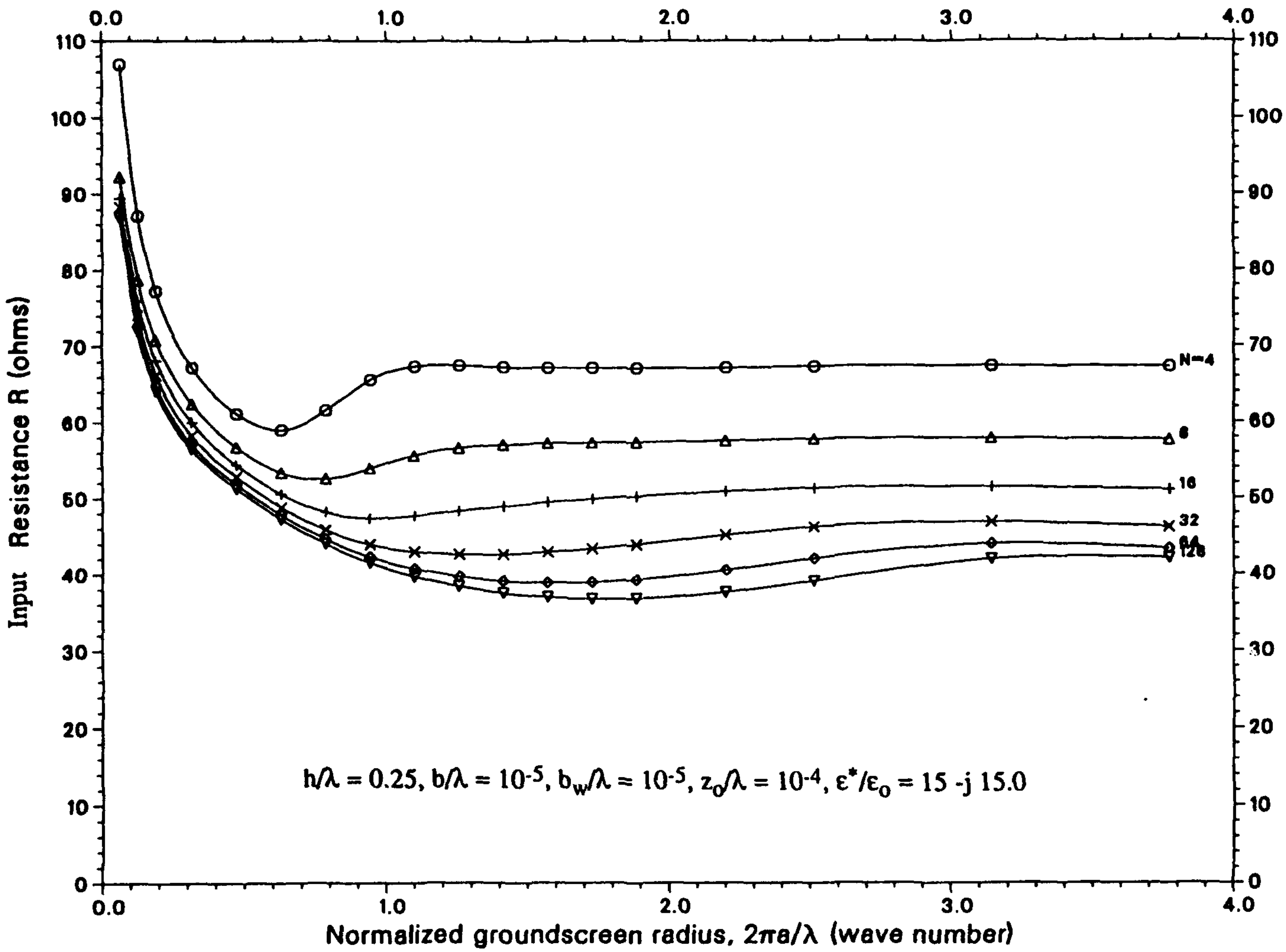

Figure 15. Input Resistance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Depth $|z_0/\lambda| = 10^{-4}$ Below Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,15.0$

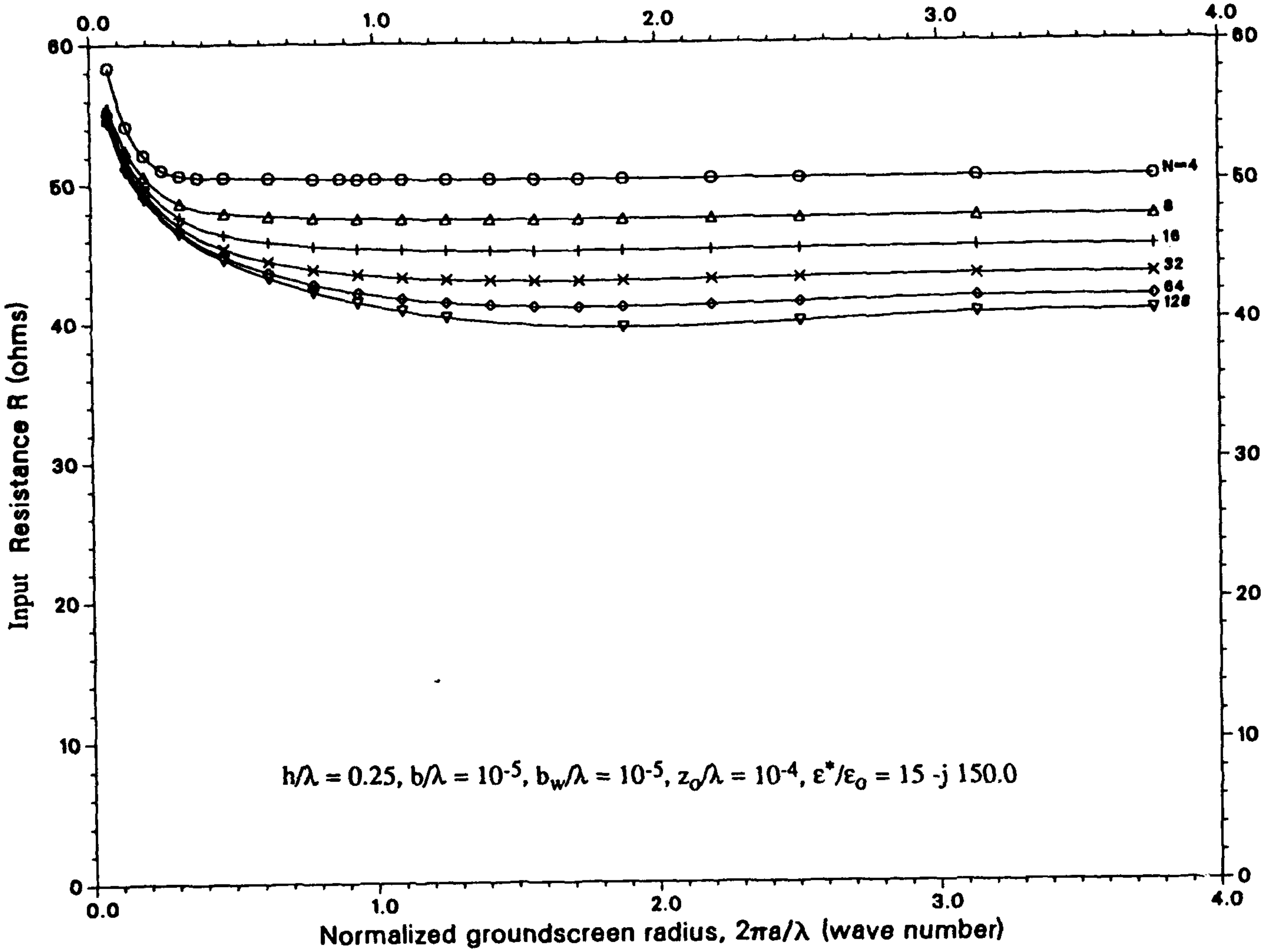

Figure 16. Input Resistance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Depth $|z_0/\lambda| = 10^{-4}$ Below Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,150.0$

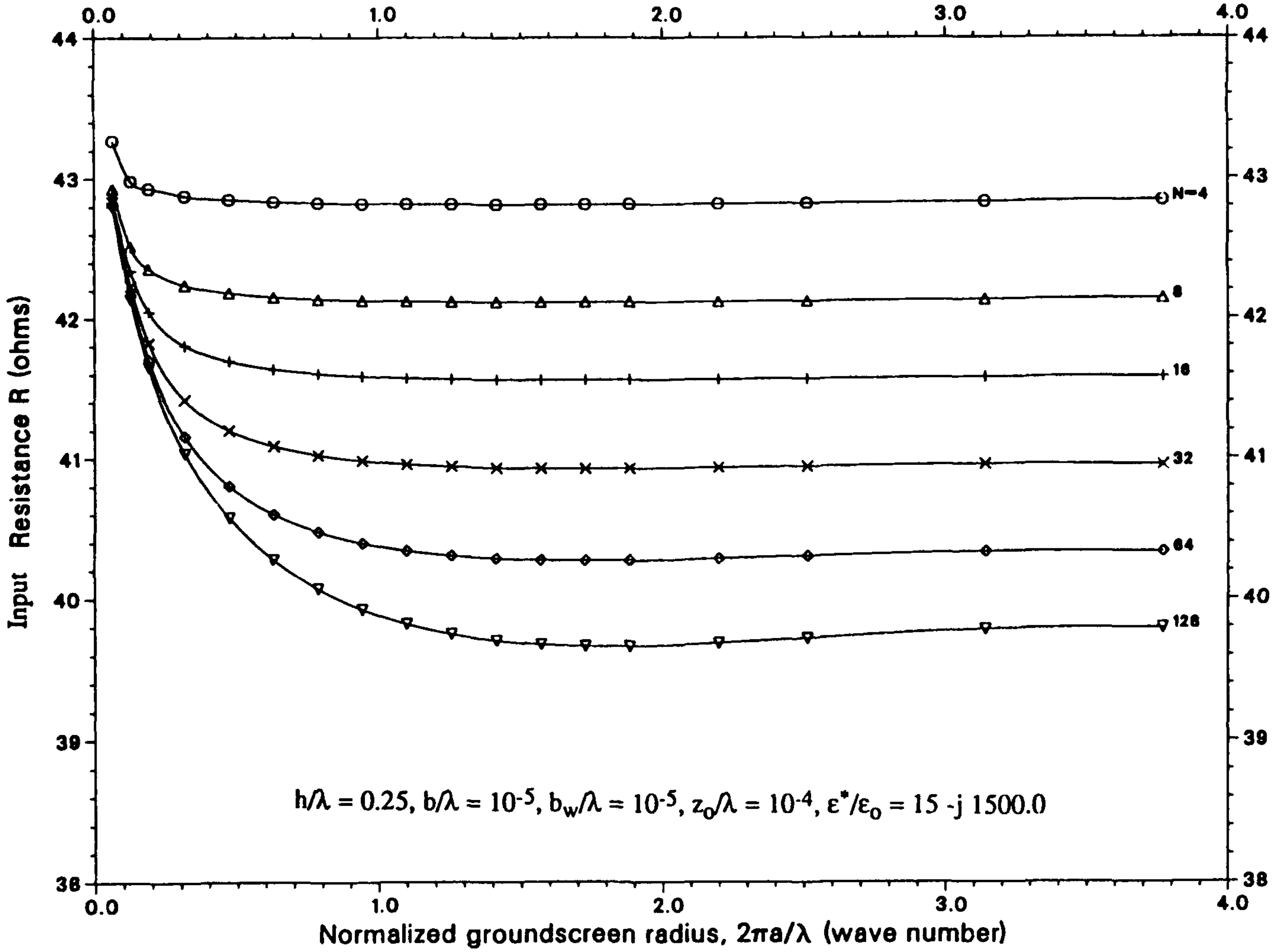

Figure 17. Input Resistance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Depth $|z_0/\lambda| = 10^{-4}$ Below Earth of Relative Permittivity $\epsilon^*/\epsilon_0 = 15 - j\ 1500.0$

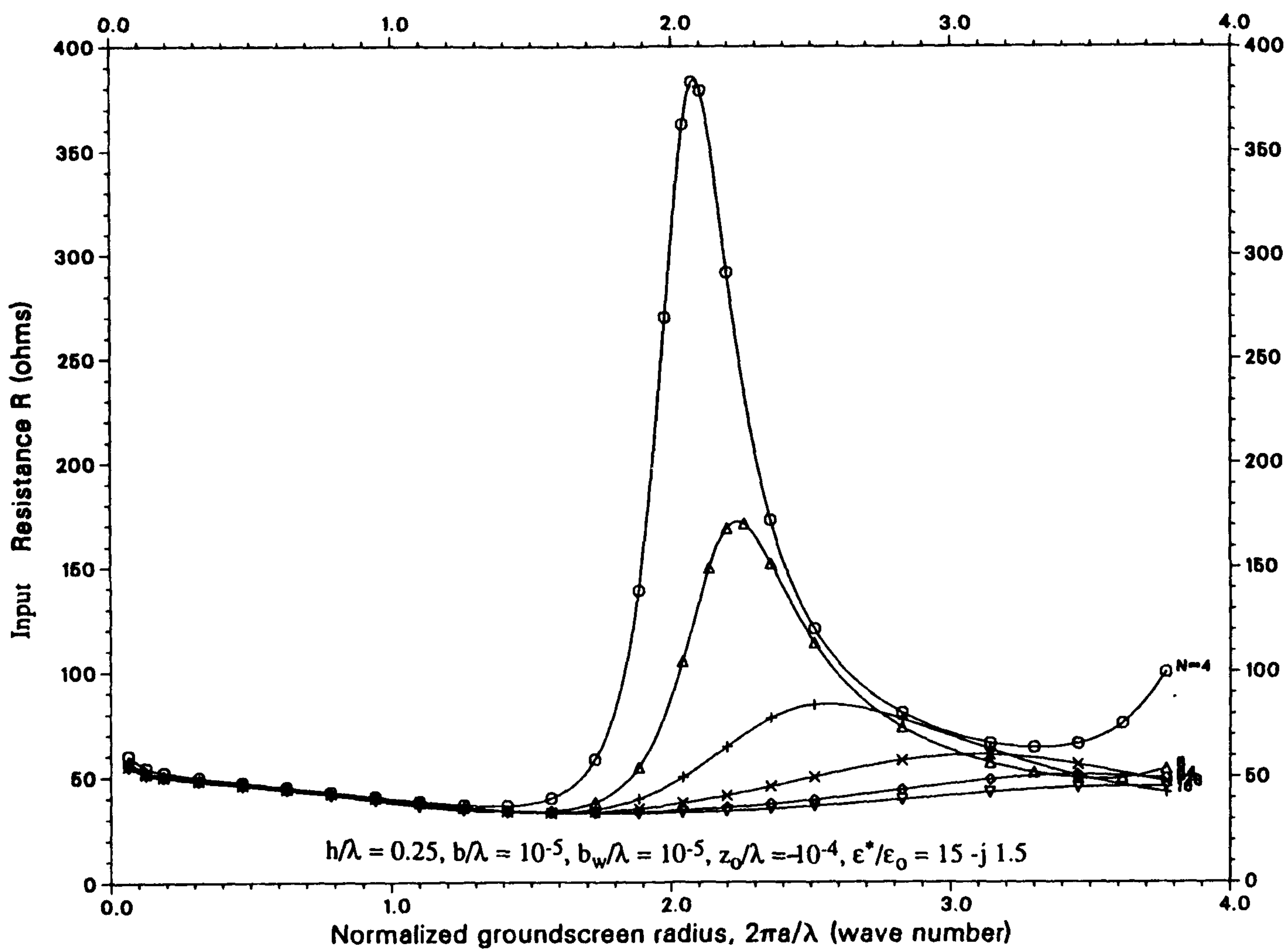

Figure 18. Input Resistance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-4}$ Above Earth of Relative Permittivity $\epsilon^*/\epsilon_0 = 15 - j\,1.5$

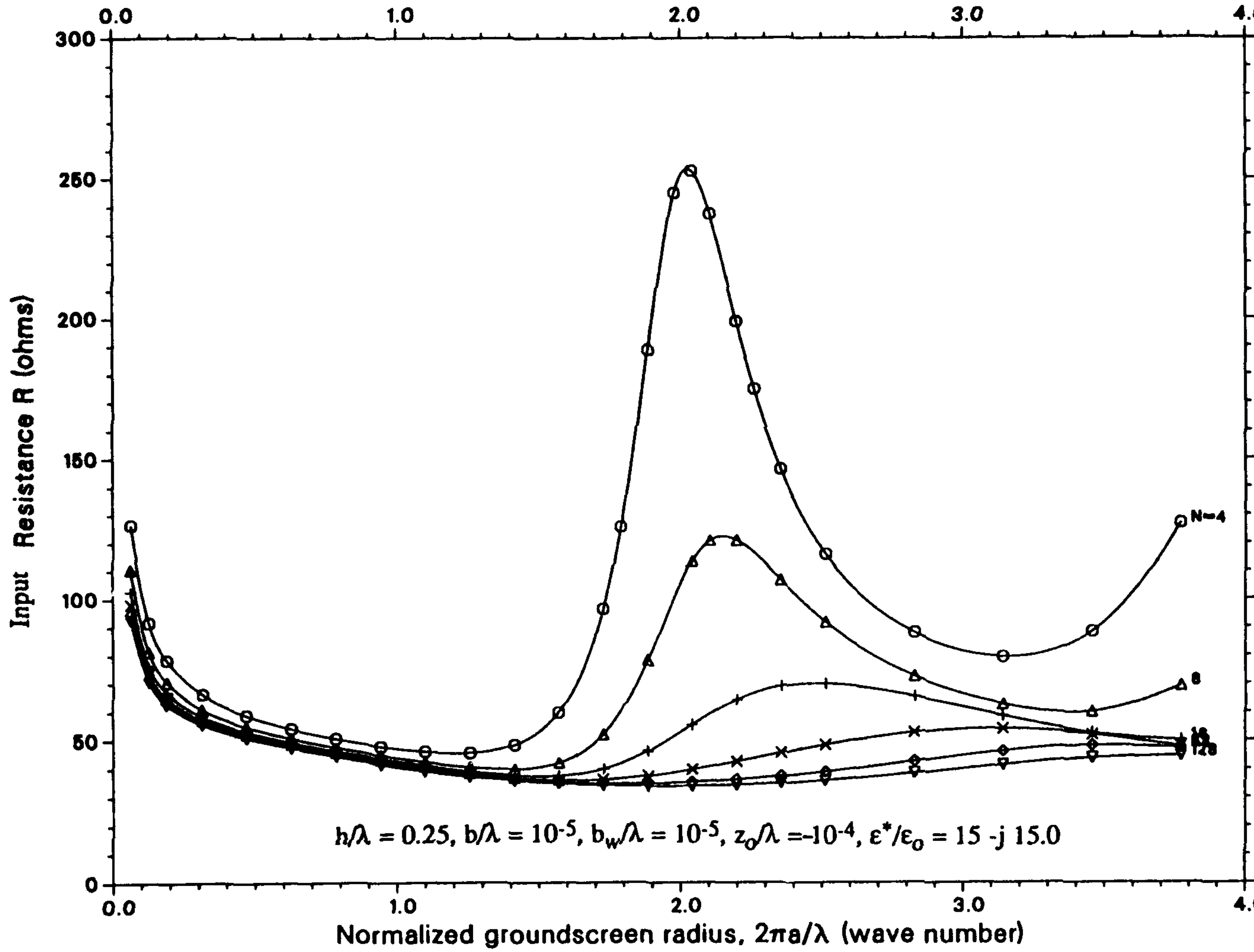

Figure 19. Input Resistance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-4}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,15.0$

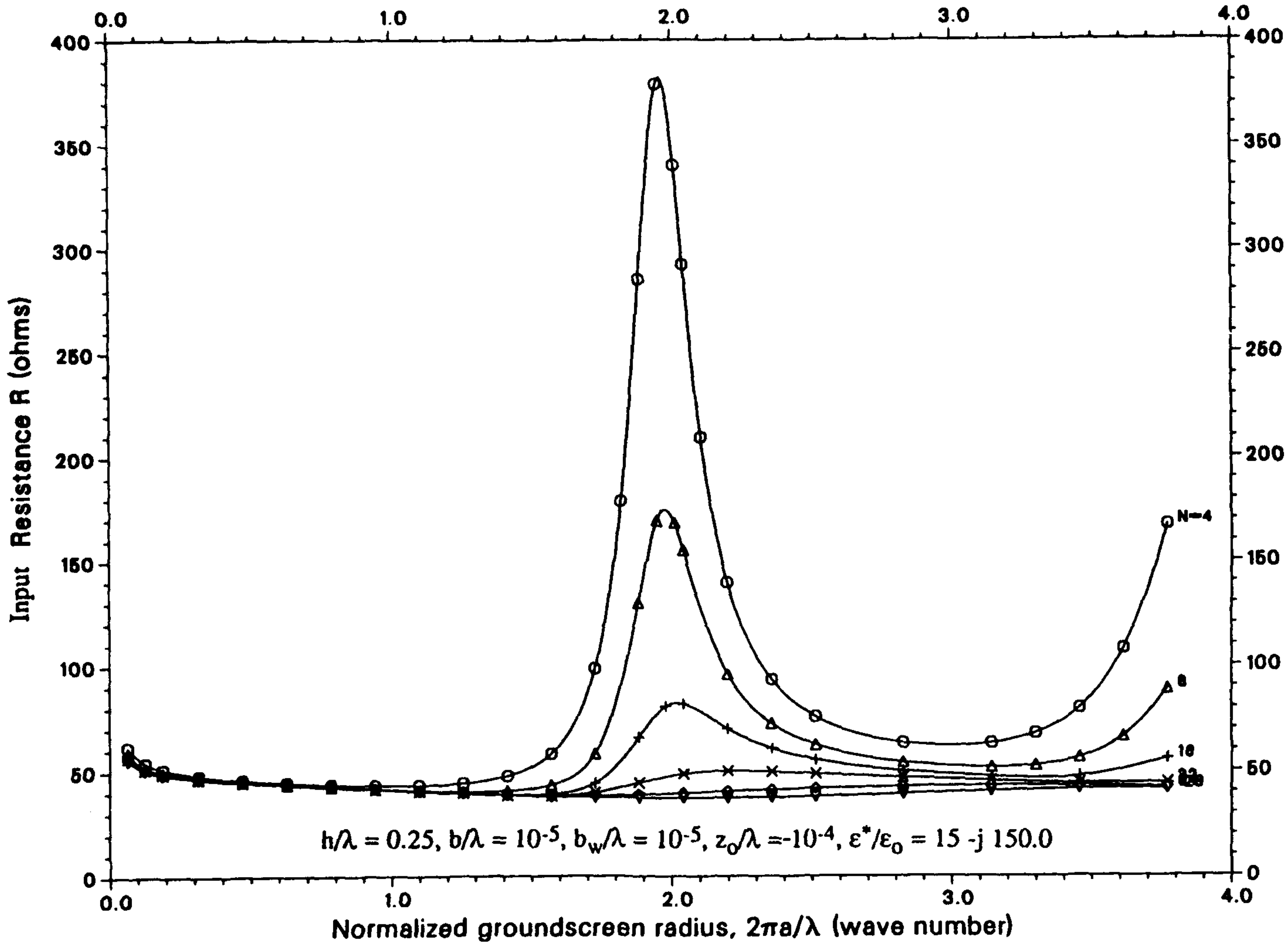

Figure 20. Input Resistance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-4}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\ 150.0$

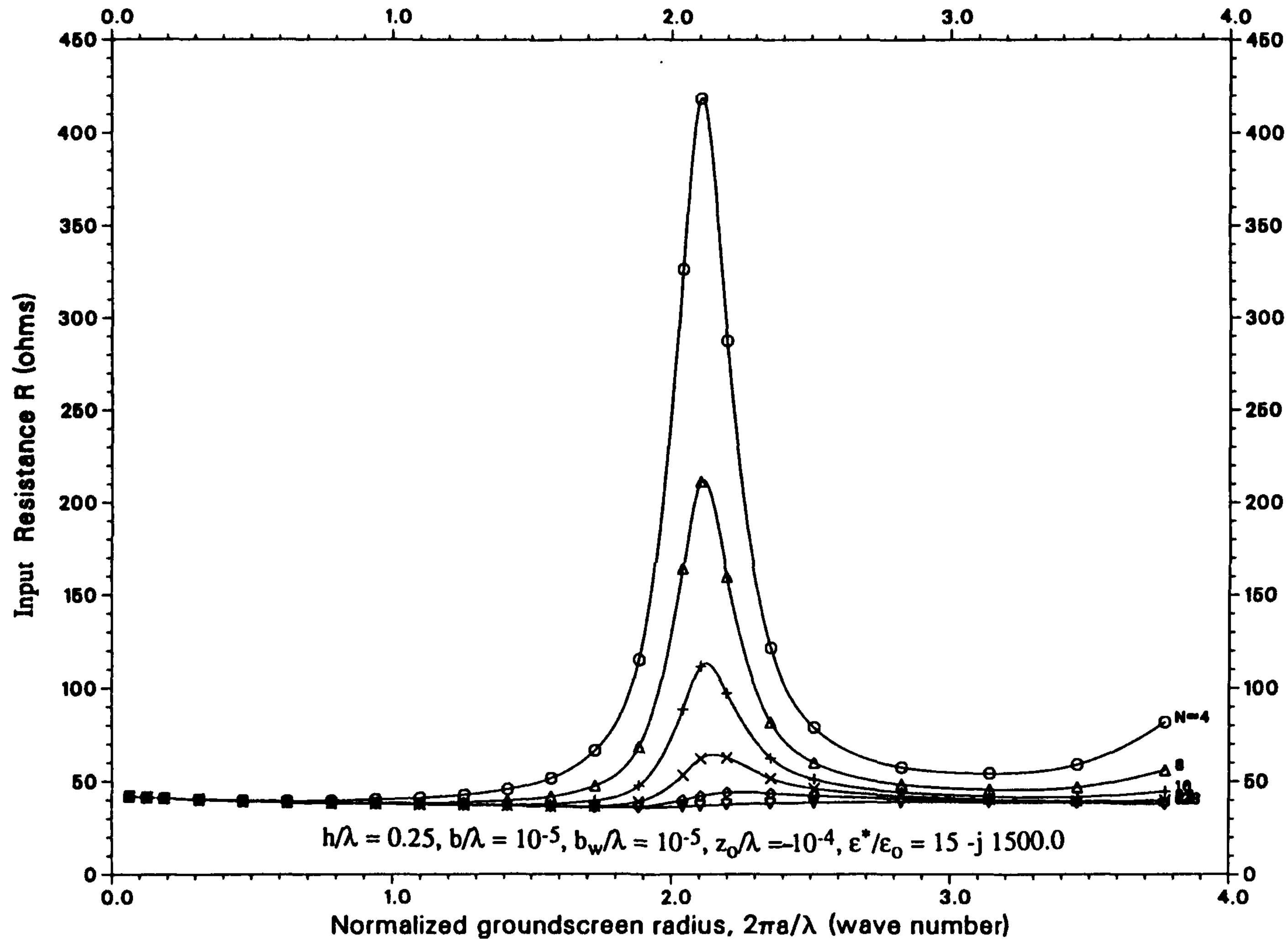

Figure 21. Input Resistance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-4}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,1500.0$

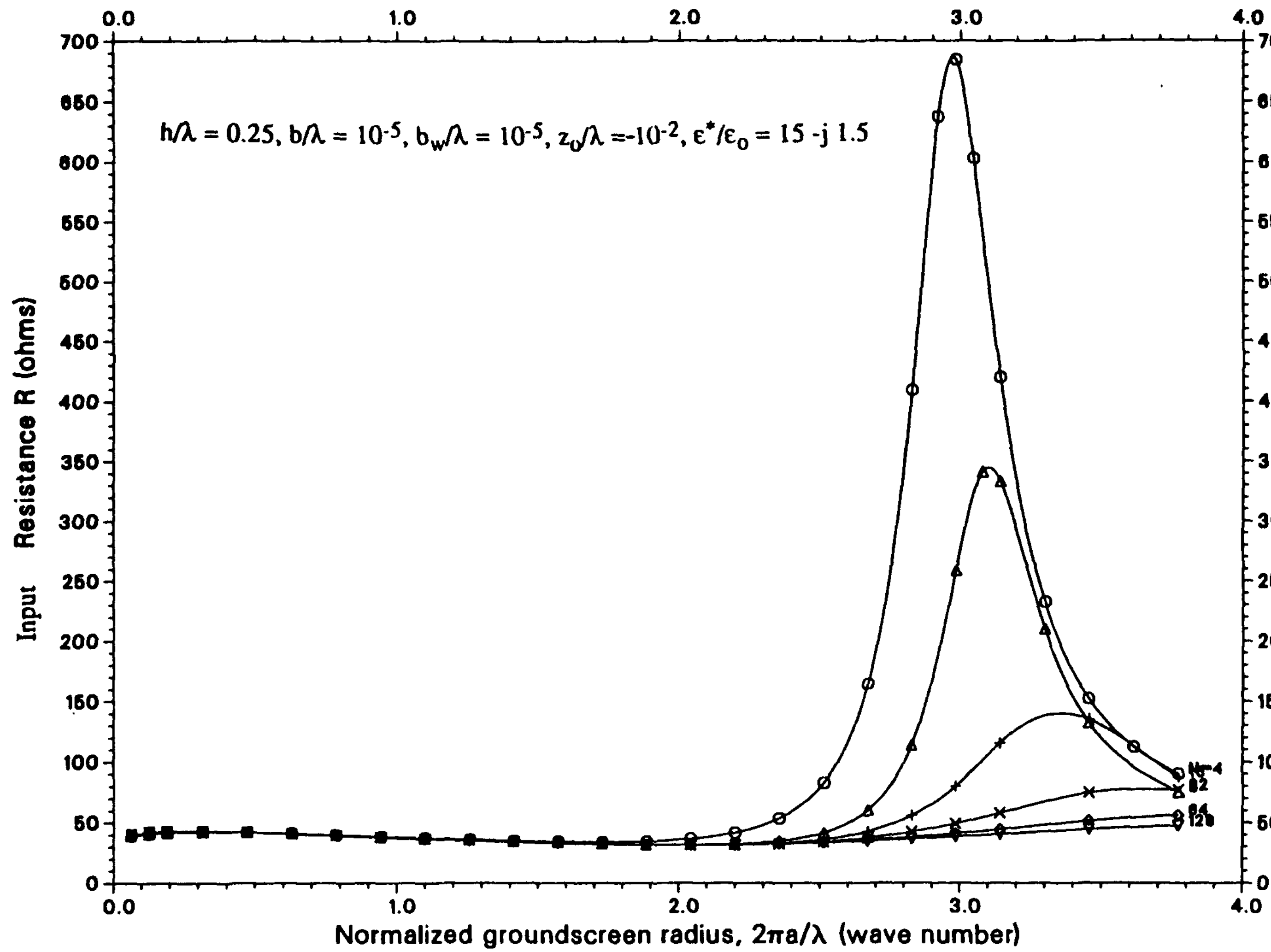

Figure 22. Input Resistance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-2}$ Above Earth of Relative Permittivity $\epsilon^*/\epsilon_0 = 15 - j\,1.5$

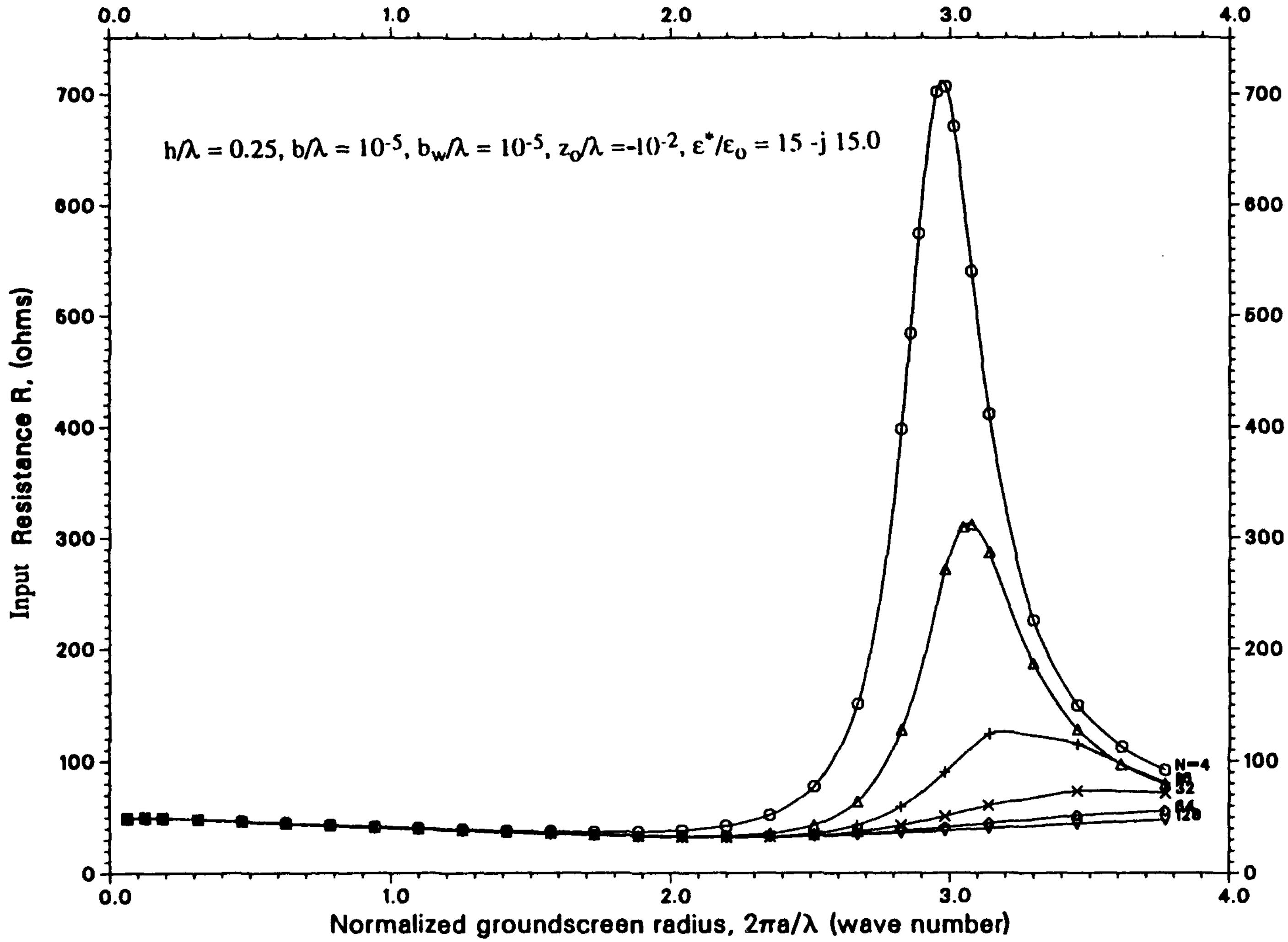

Figure 23. Input Resistance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_o/\lambda| = 10^{-2}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\ 15.0$

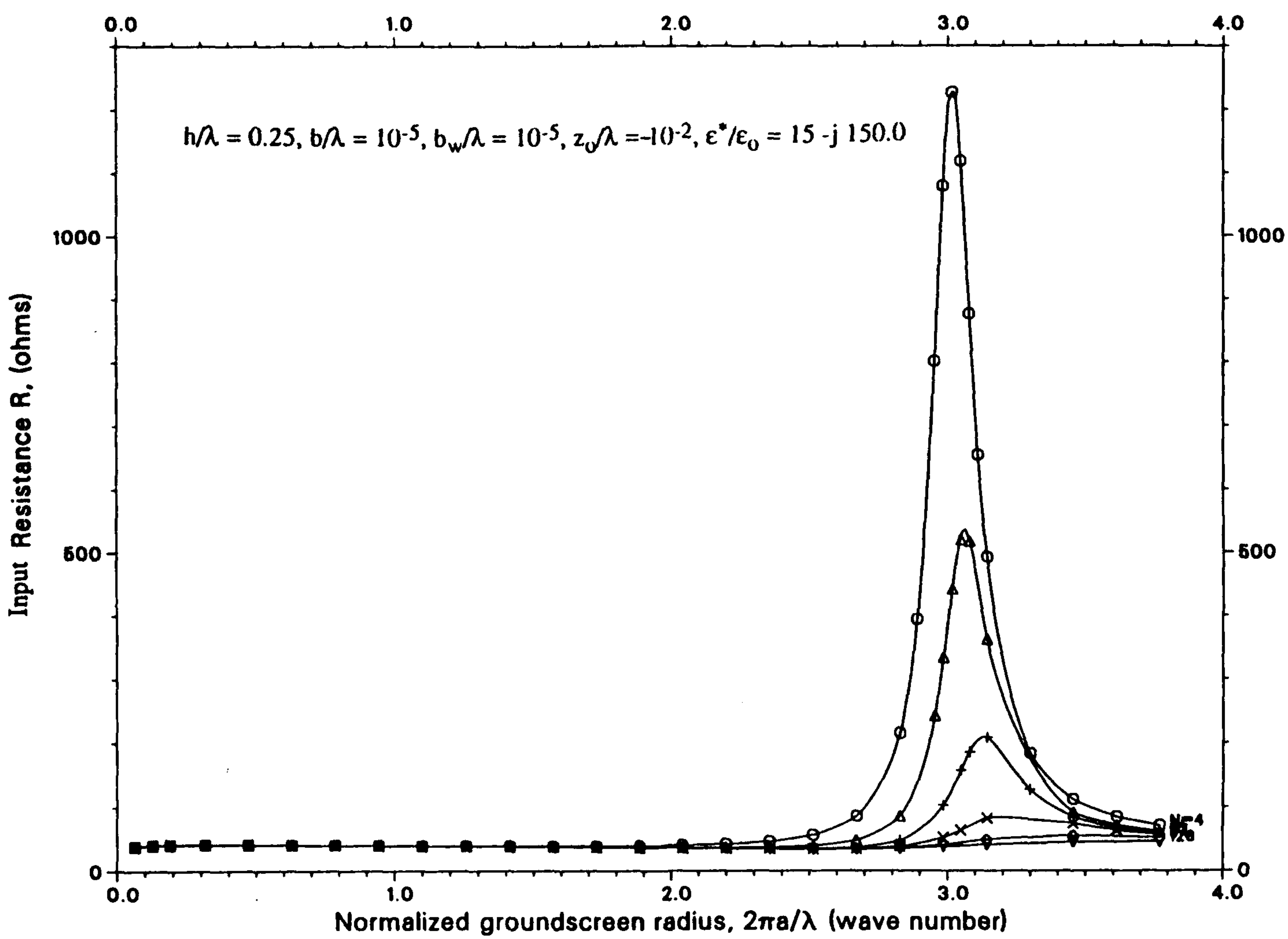

Figure 24. Input Resistance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-2}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,150.0$

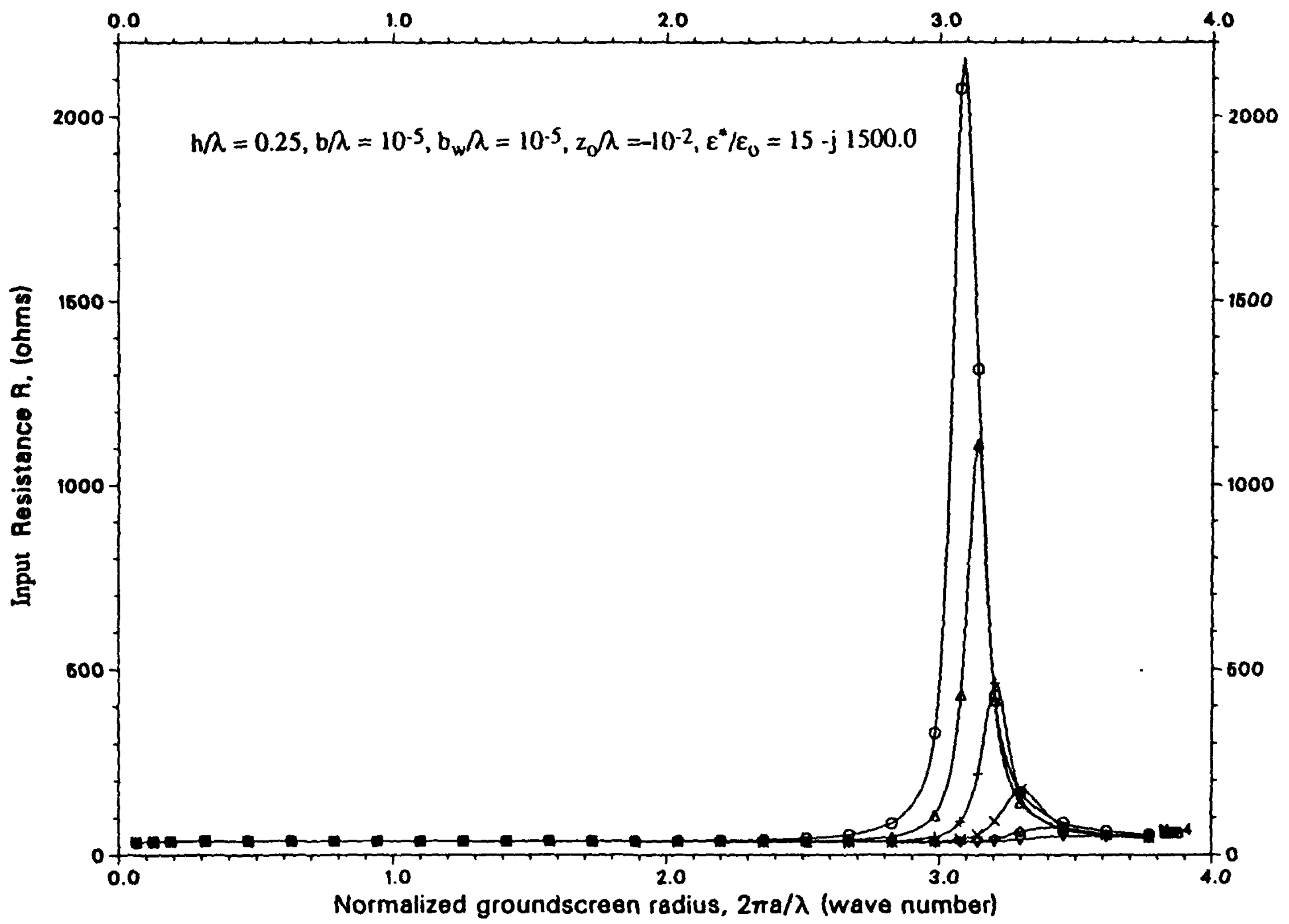

Figure 25. Input Resistance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-2}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,1500.0$

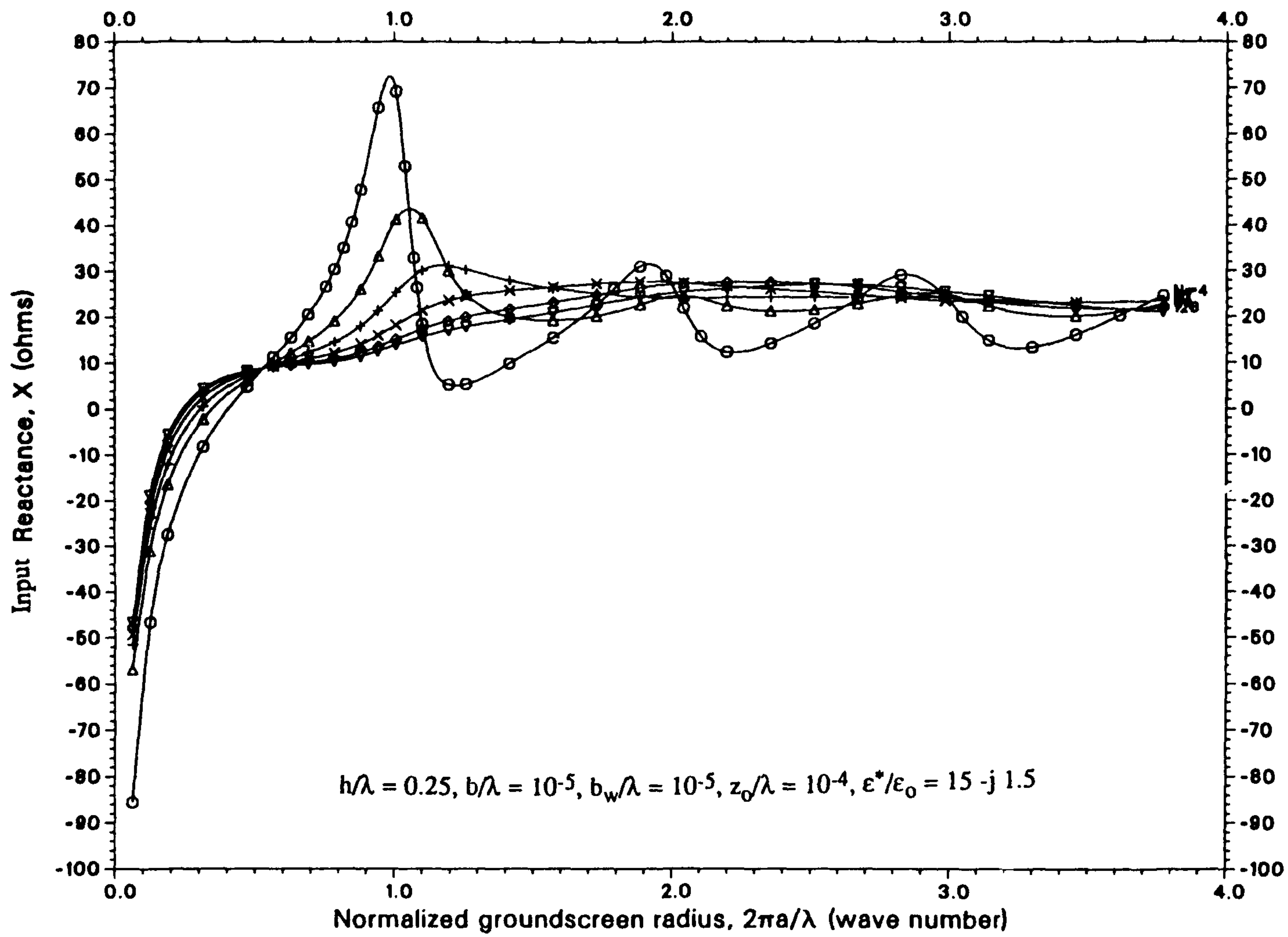

Figure 26. Input Reactance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Depth $|z_0/\lambda| = 10^{-4}$ Below Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,1.5$

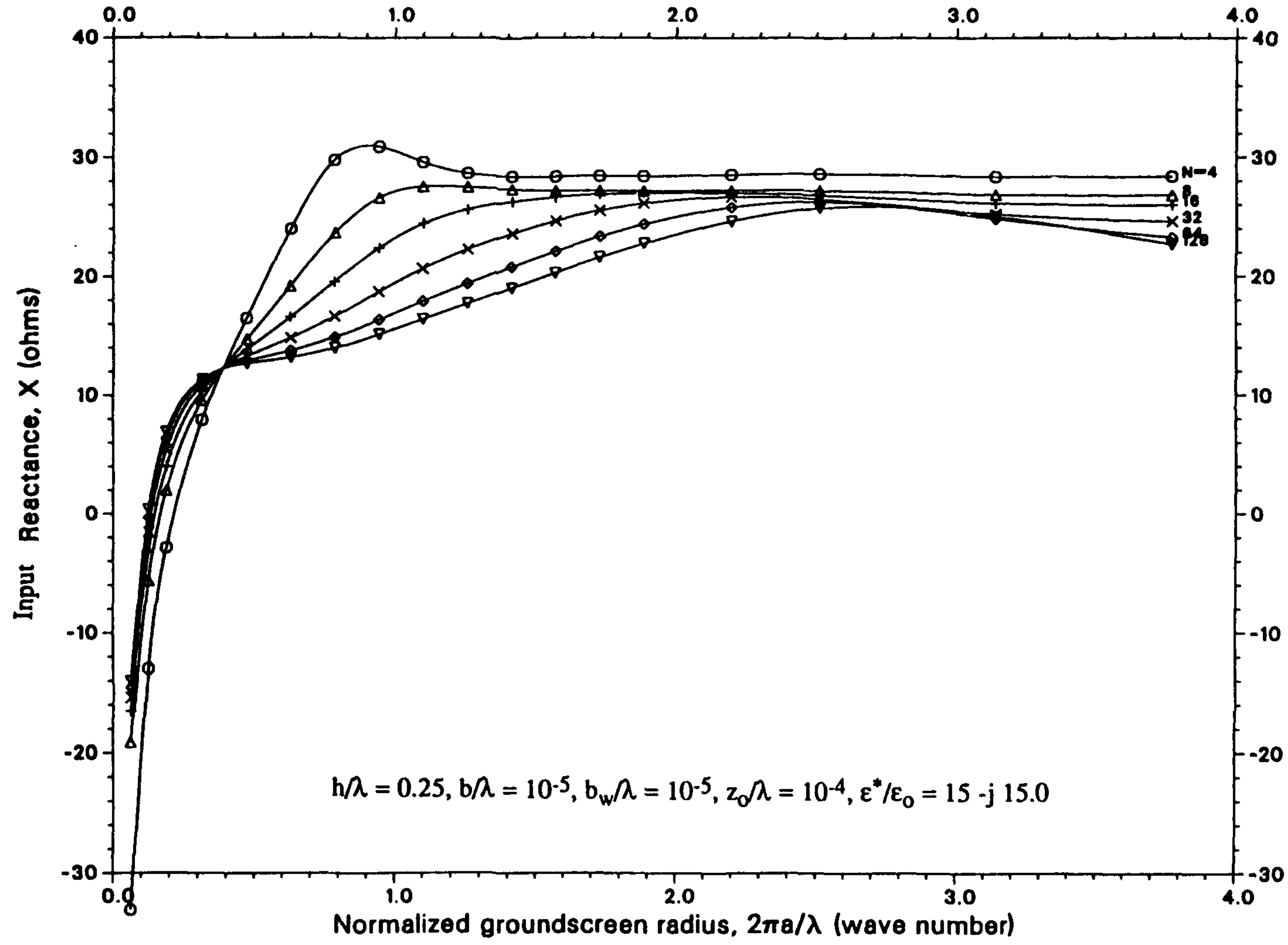

Figure 27. Input Reactance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Depth $|z_0/\lambda| = 10^{-4}$ Below Earth of Relative Permittivity $\epsilon^*/\epsilon_0 = 15 - j\,15.0$

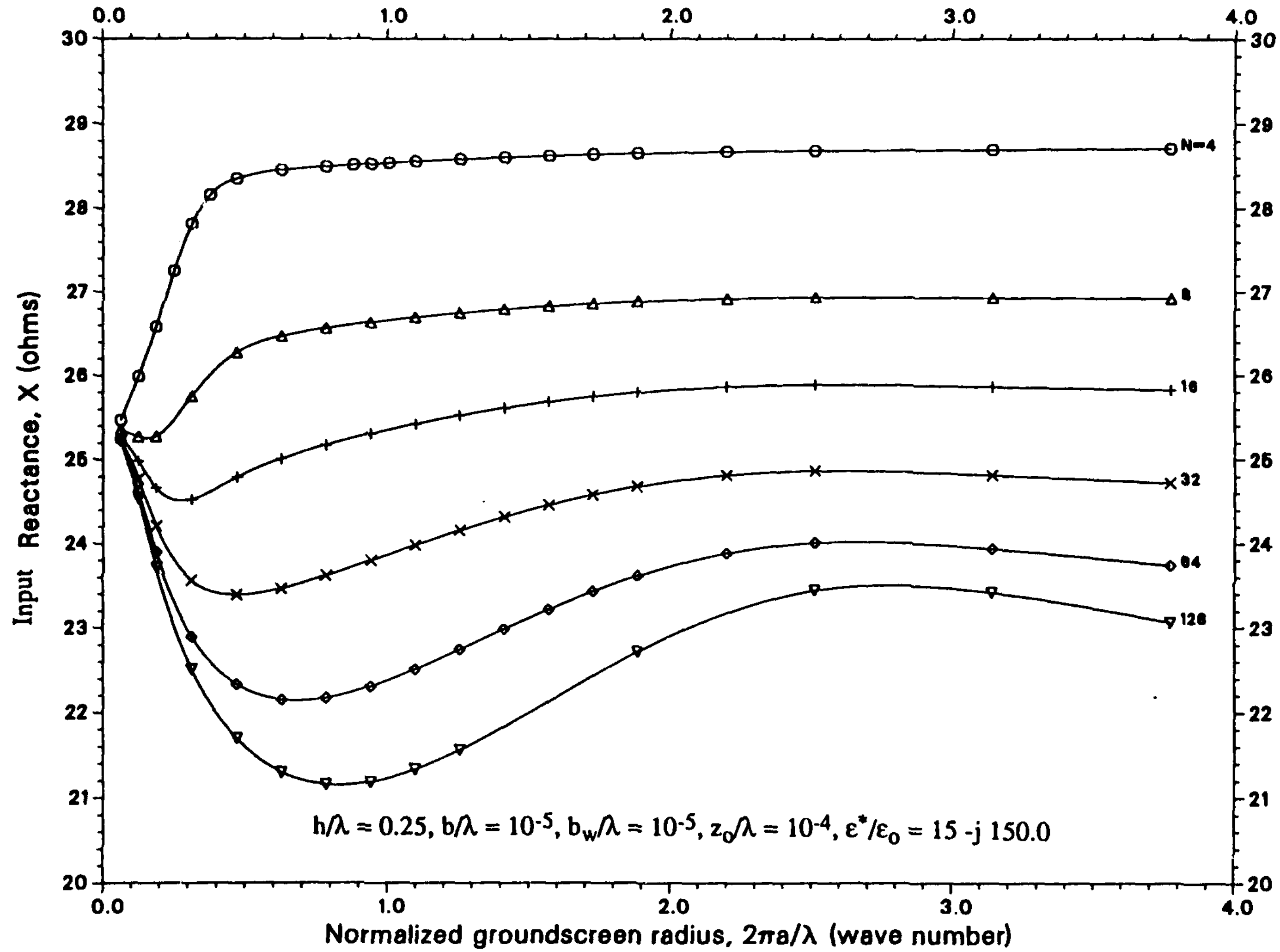

Figure 28. Input Reactance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Depth $|z_0/\lambda| = 10^{-4}$ Below Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\ 150.0$

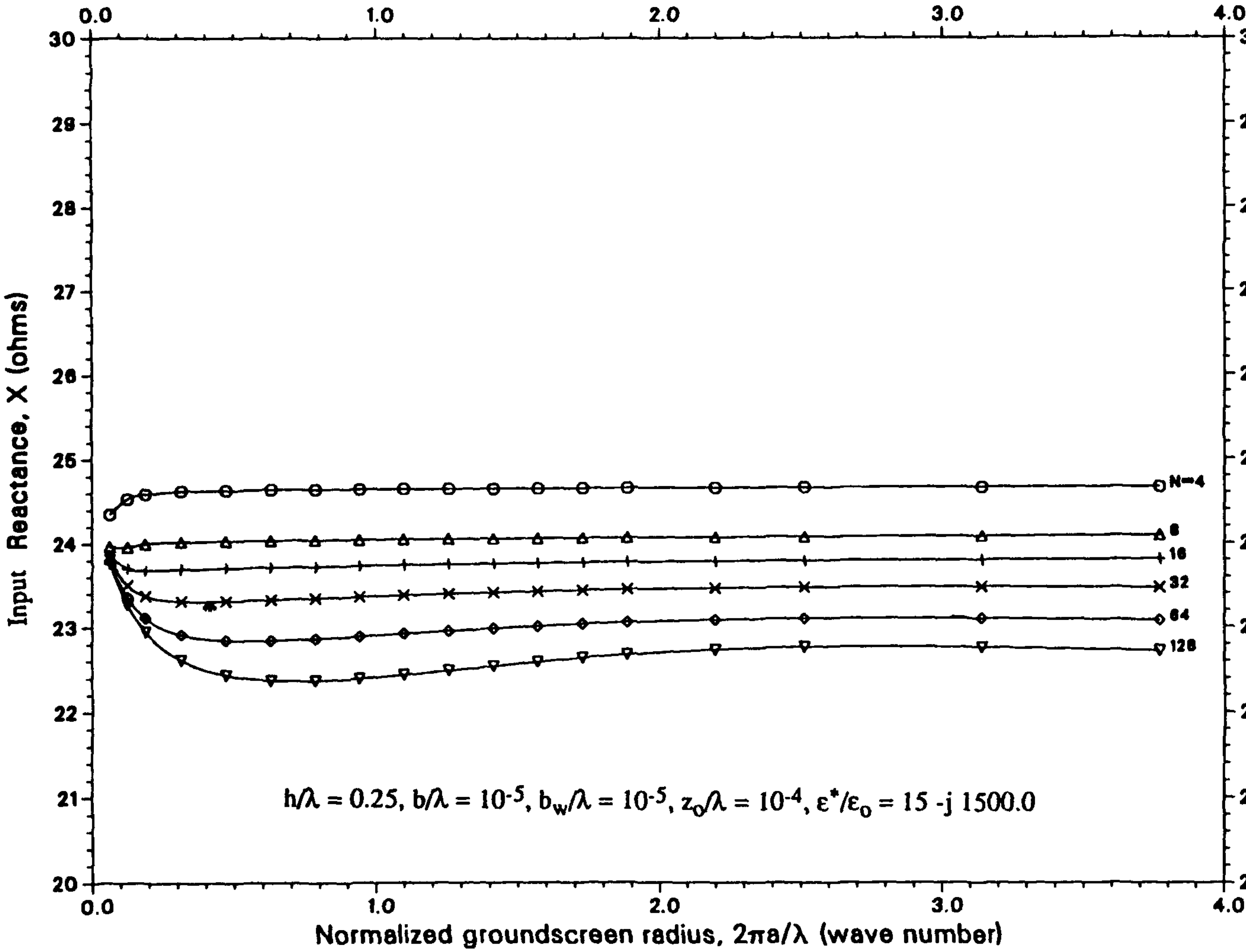

Figure 29. Input Reactance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Depth $|z_0/\lambda| = 10^{-4}$ Below Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\ 1500.0$

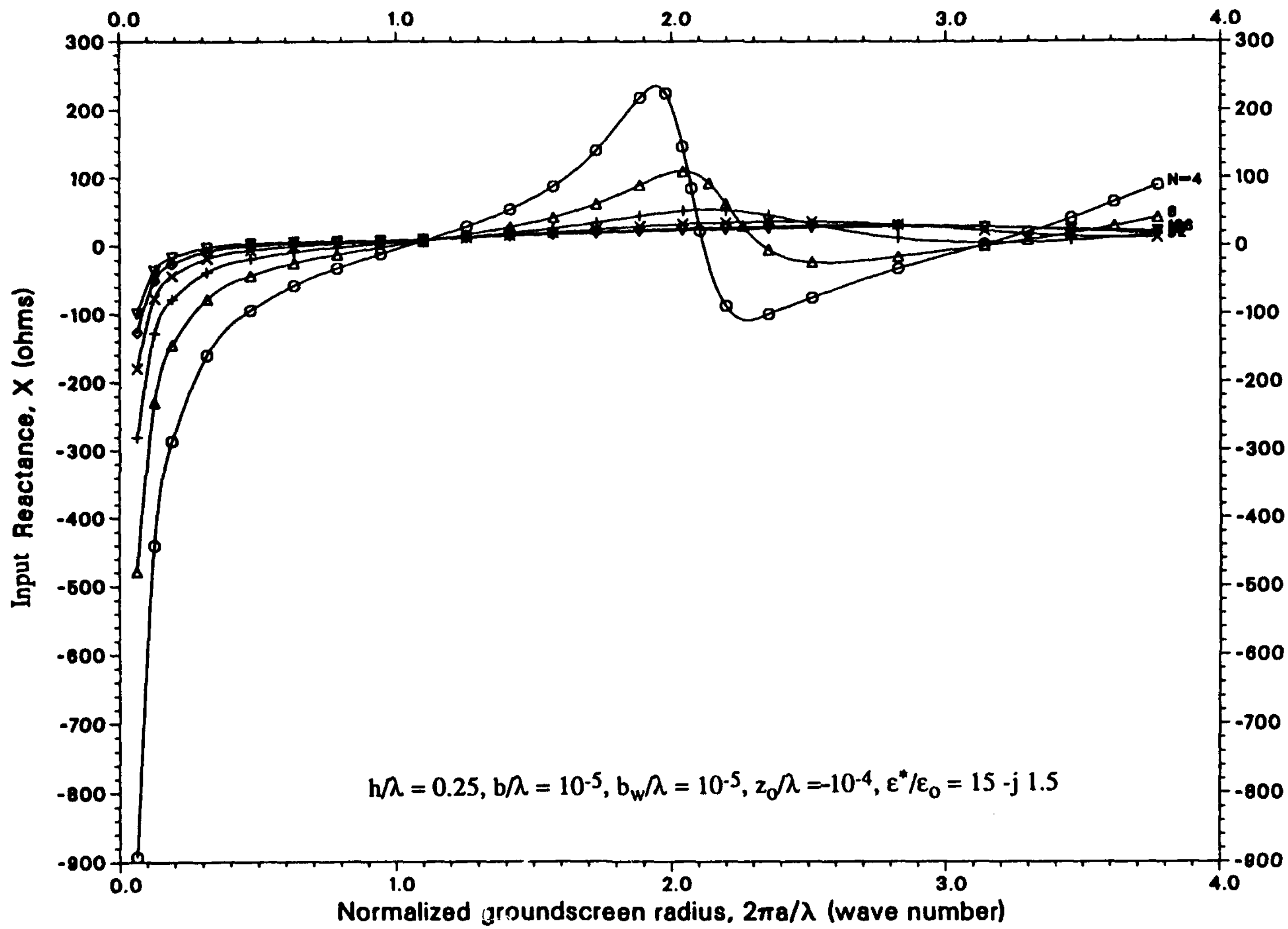

Figure 30. Input Reactance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-4}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,1.5$

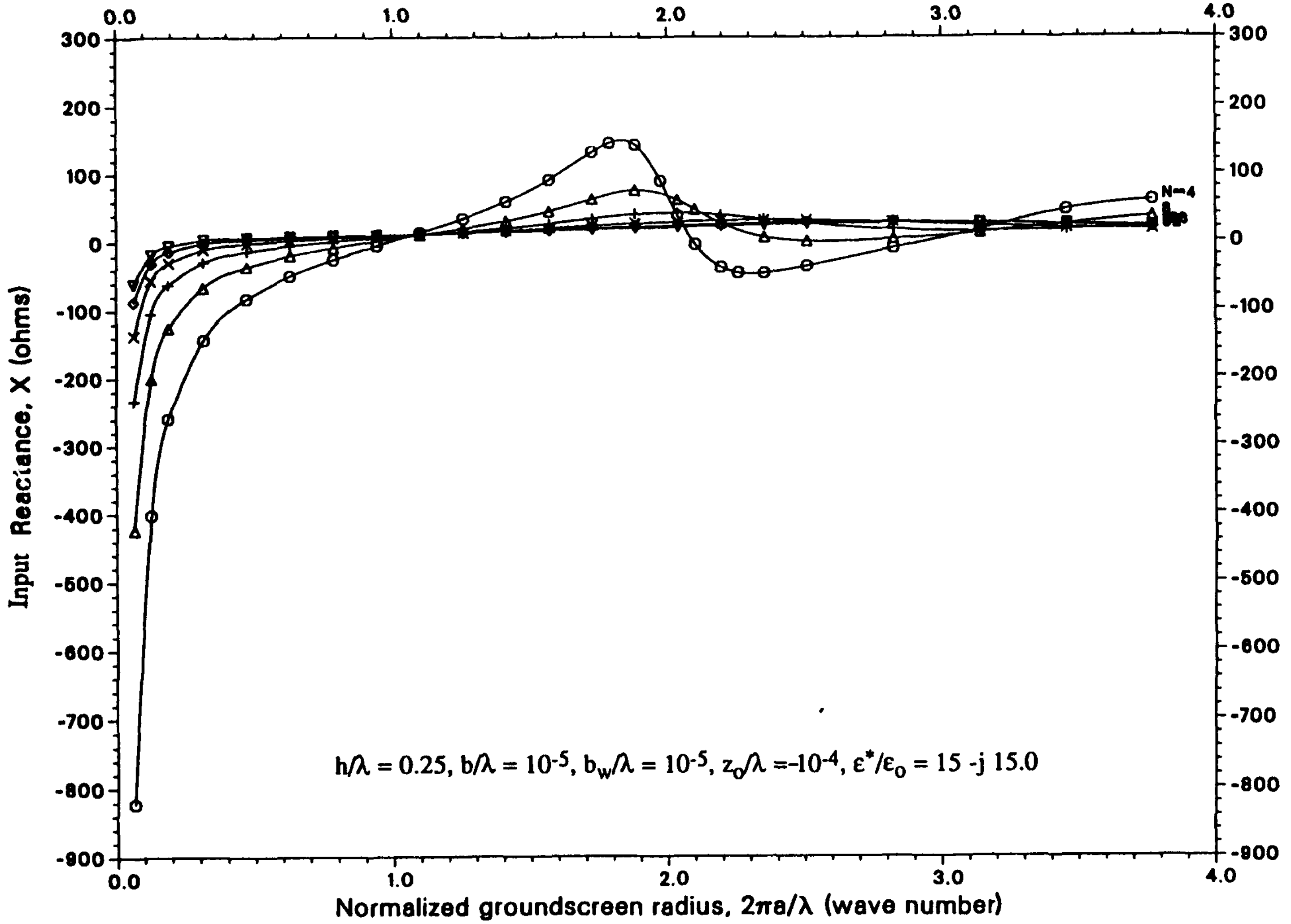

Figure 31. Input Reactance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-4}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,15.0$

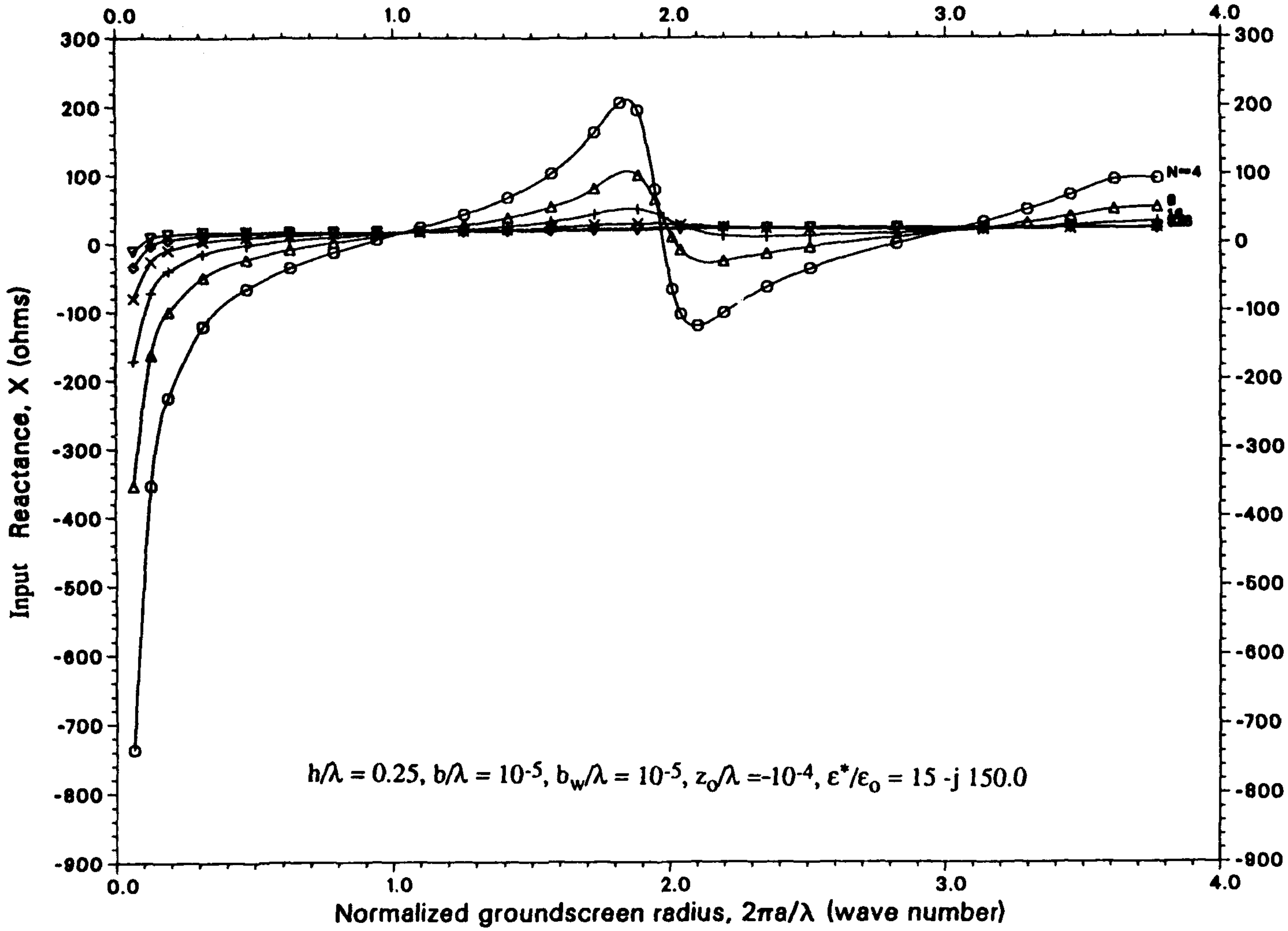

Figure 32. Input Reactance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-4}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,150.0$

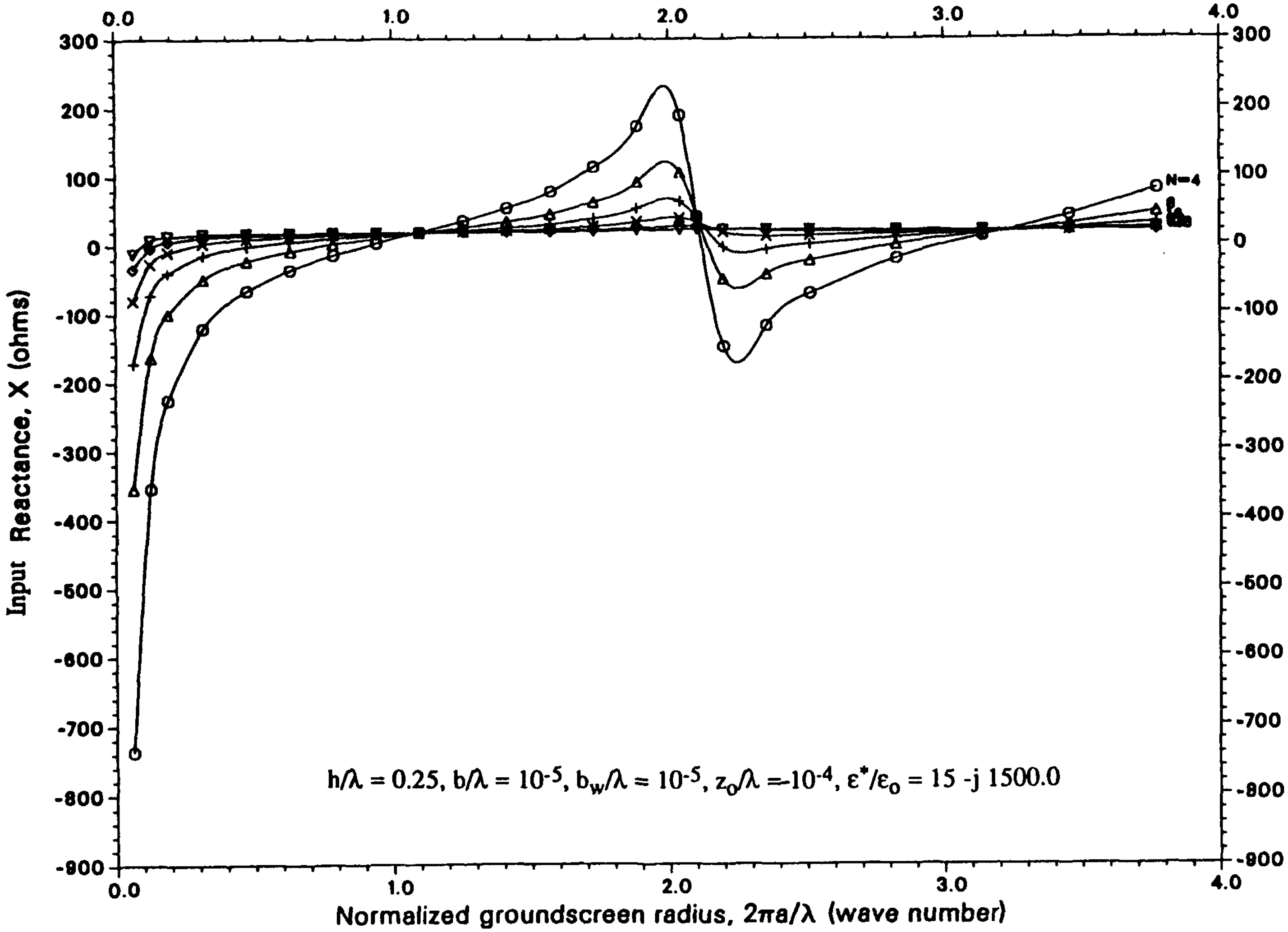

Figure 33. Input Reactance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_o/\lambda| = 10^{-4}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_o = 15 - j\,1500.0$

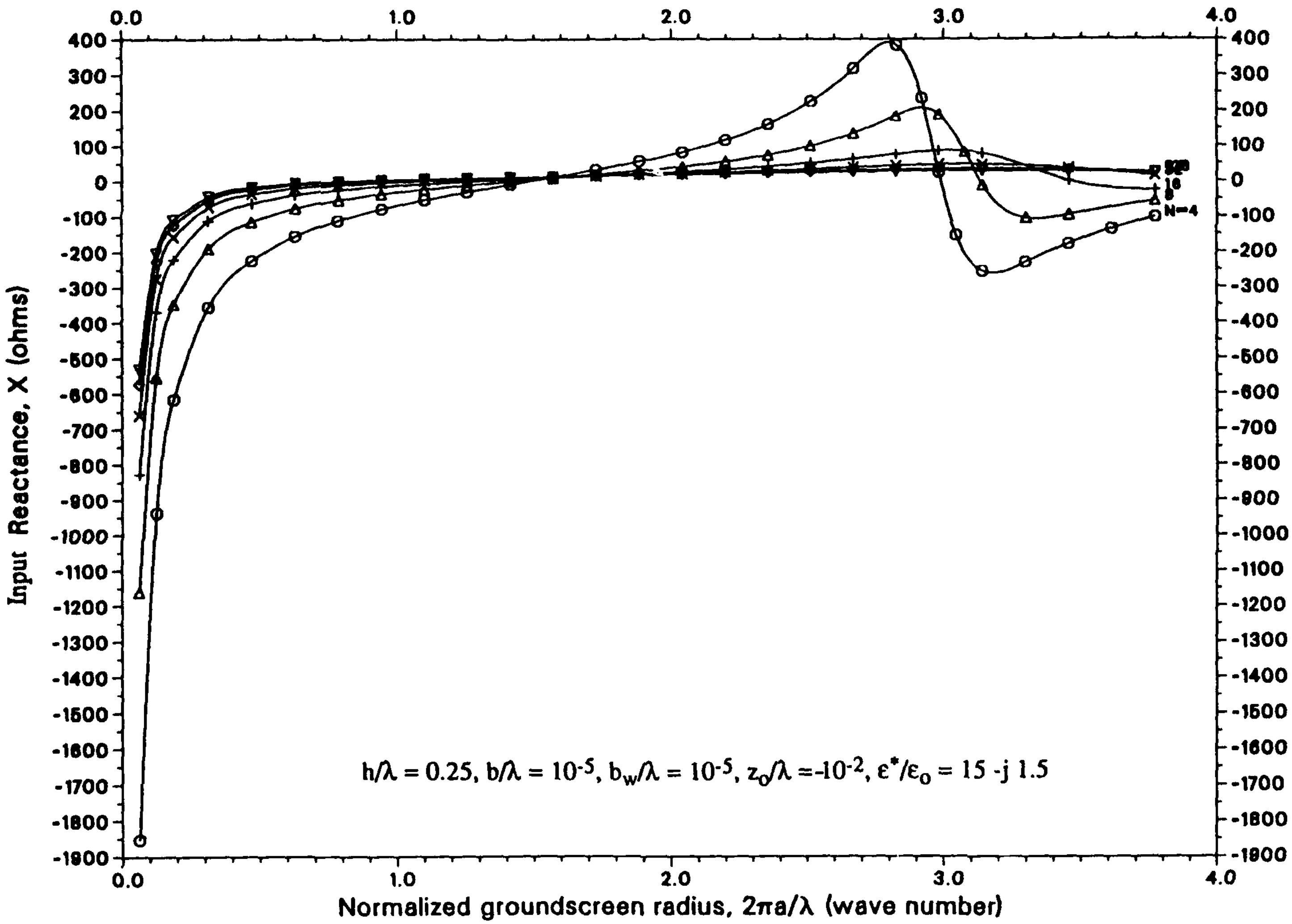

Figure 34. Input Reactance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-2}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,1.5$

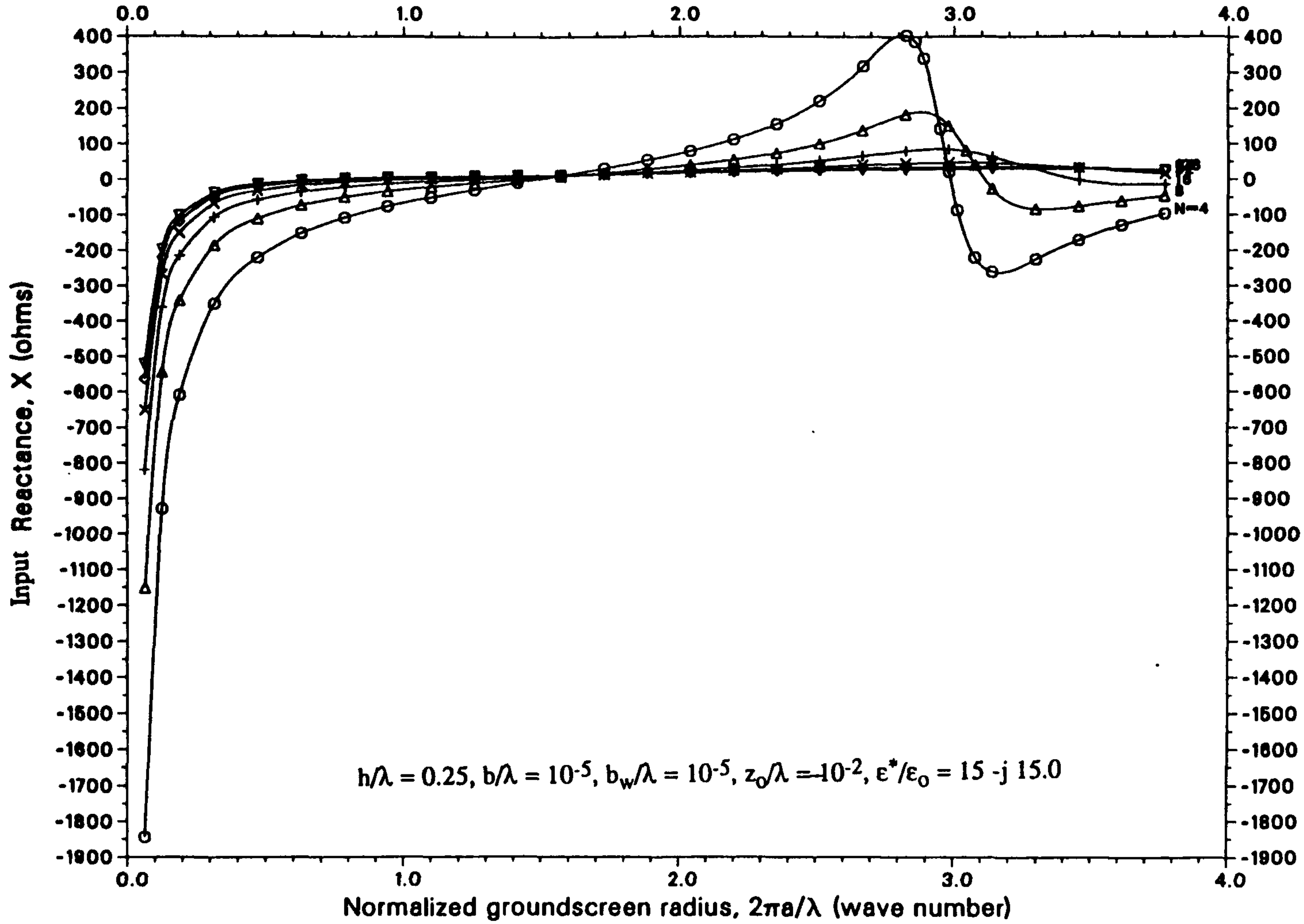

Figure 35. Input Reactance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-2}$ Above Earth of Relative Permittivity $\epsilon^*/\epsilon_0 = 15 - j\ 15.0$

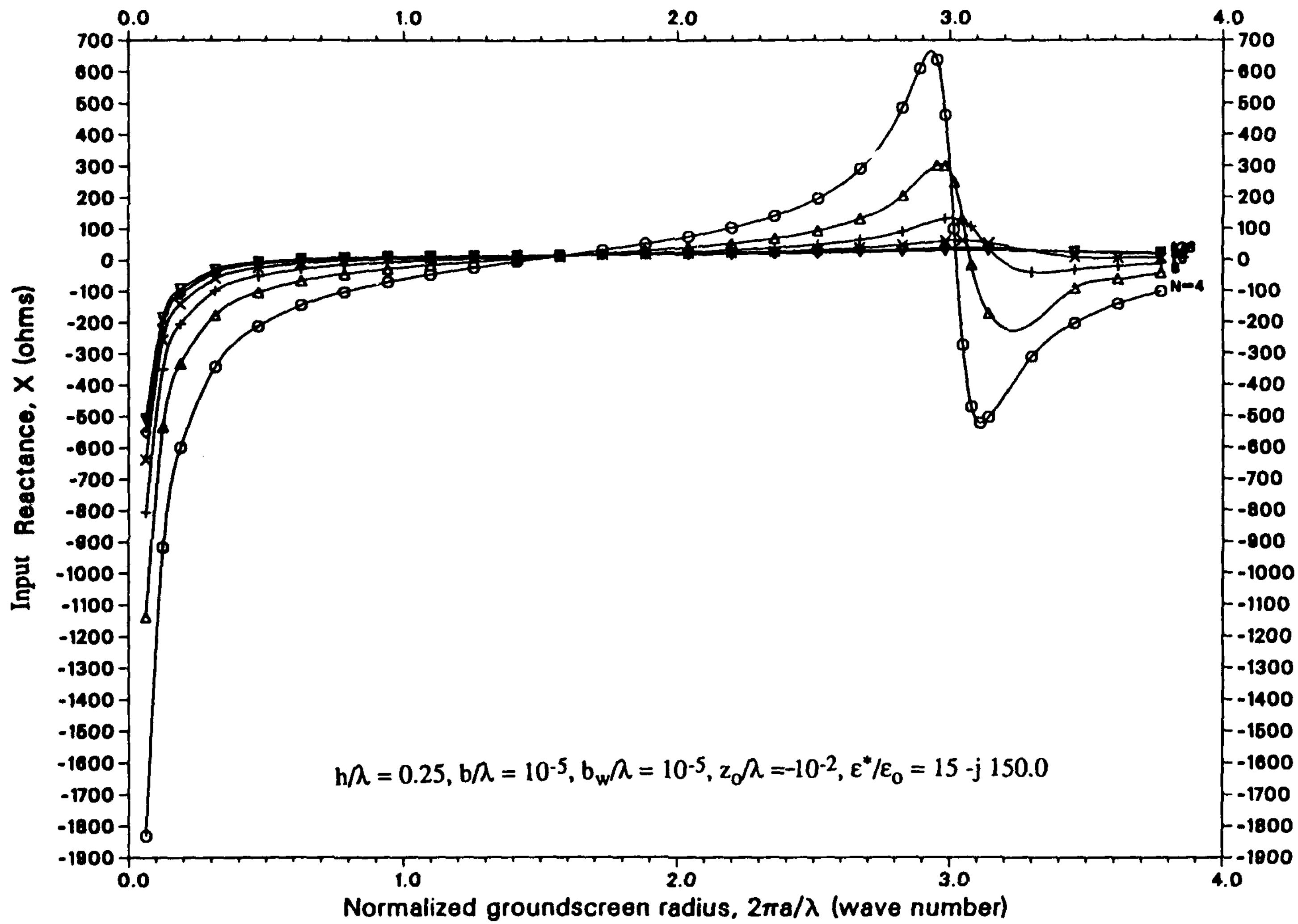

Figure 36. Input Reactance of a Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_0/\lambda| = 10^{-2}$ Above Earth of Relative Permittivity $\varepsilon^*/\varepsilon_0 = 15 - j\,150.0$

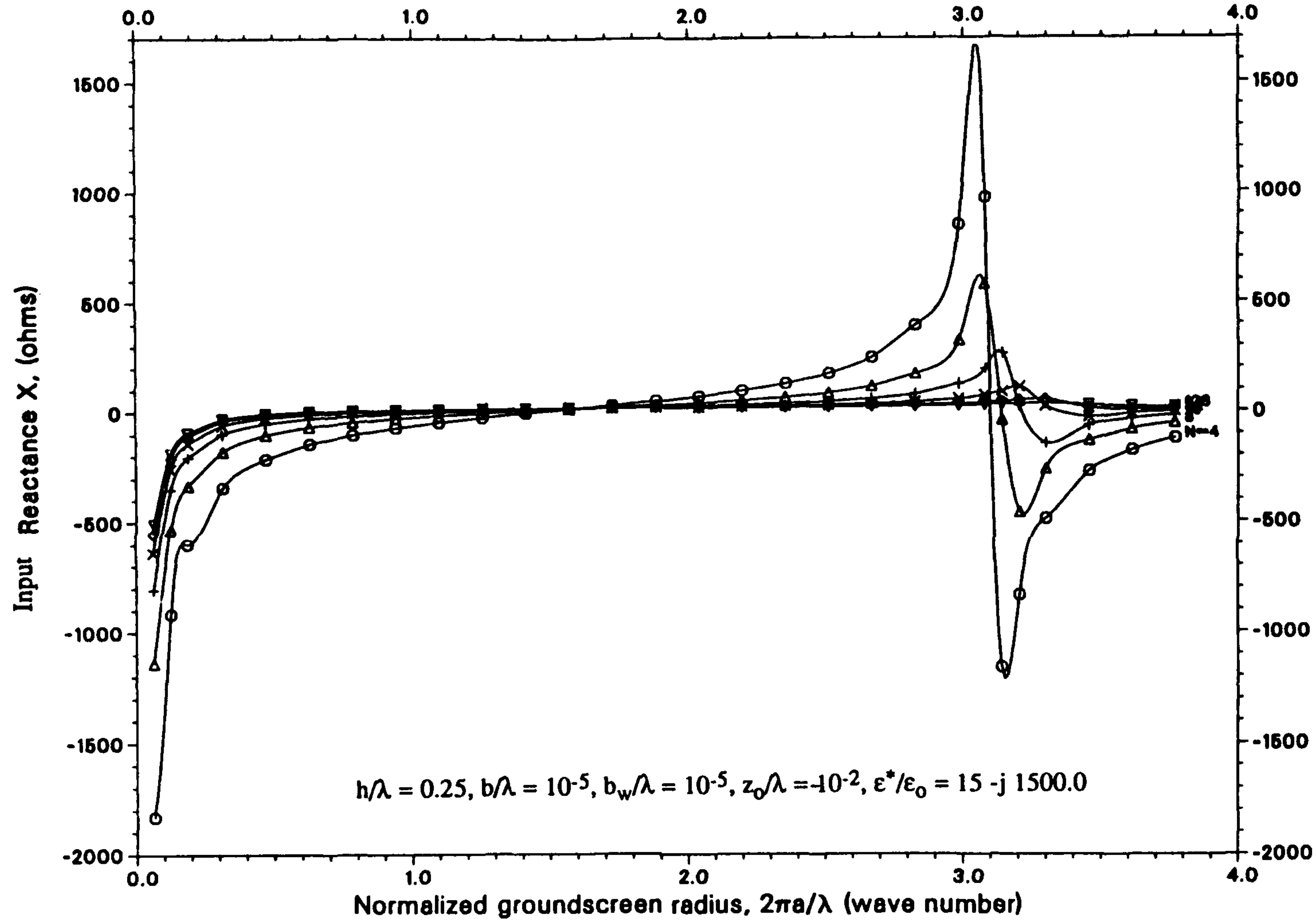

Figure 37. Input Reactance of A Quarter-Wave Monopole Element with a Radial-Wire Ground Plane at a Height $|z_o / \lambda| = 10^{-2}$ Above Earth of Relative Permittivity $\varepsilon^* / \varepsilon_o = 15 - j\,1500.0$

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